NISTIR 5919

A Computer Analysis of the Moisture Performance of Roof Constructions in the U.S. DOE Moisture Control Handbook

G.A. Tsongas & B.A. Thornton
D.M. Burch & G.N. Walton

December 1996

Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

U.S. Department of Commerce
Michael Kantor, *Secretary*
Technology Administration
Mary L. Good, *Under Secretary for Technology*
National Institute of Standards and Technology
Arati Prabhakar, *Director*

U.S. Department of Energy
Washington, D.C., 20858

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

A new mathematical model, called the MOIST Attic Model, that predicts the transfer of heat and moisture in ventilated or unventilated roof cavities is presented. The model includes both molecular diffusion and capillary transfer within the materials and also calculates the indoor relative humidity, the ceiling air leakage rate, and the roof cavity ventilation rate at hourly time steps. This computer simulation model can be used to assess the moisture performance of open attics as well as cathedral ceilings. Typical applications include estimating the variation throughout a year of the moisture content of roof wood members, of roof cavity surface relative humidities, and of ceiling heat flux. In the present study, the model is used to predict the moisture performance of a current practice site-built prototype house with 15 different roof designs constructed in compliance with the *U.S. DOE Moisture Control Handbook* in cold (heating), mixed, and cooling (hot and humid) climates. These open attic or cathedral ceiling roof constructions were intended to be the best designs to minimize moisture accumulation, thereby preventing material degradation, mold and mildew growth, and loss in thermal performance. But prior to this study, their moisture performance had not been checked with a moisture model. Thus this computer simulation study of their performance was undertaken. For each of the 15 roof designs, attention was focused on the peak values of the plywood roof sheathing moisture content and the relative humidity at the bottom of the insulation adjacent to the various ceilings where mold and mildew might grow. Findings of the study regarding the moisture performance of the 15 designs, as well as roof design suggestions, are presented along with recommendations for further study.

KEYWORDS

Air Flow, Attics, Building Codes, Building Research, Guidelines and Practices, Mathematical Analysis, Mathematical Modeling, Moisture, Moisture Analysis, Moisture Control, Moisture Modeling, Mold and Mildew, Roofs, Roof Cavities, Roof or Attic Ventilation, and Site-Built Housing.

EXECUTIVE SUMMARY

A new mathematical model is presented that predicts moisture and heat transfer in ventilated roof cavities such as attics and cathedral ceilings. The model performs a transient moisture and heat balance as a function of time of year and includes the storage of moisture and heat at construction layers. The model includes both molecular diffusion and capillary transfer within the materials. Radiation exchange among the ventilated cavity surfaces is predicted using a mean-radiant-temperature-network model. Latent heat (i.e., the effect of water evaporating from one place and condensing at another place) is distributed within the materials. Air flow from the house into the ventilated cavity is predicted using a stack effect model with aggregated effective leakage areas representing the air leakage resistances of the house thermal envelope below the ceiling, the ceiling, and the roof. Air exchange between the ventilated cavity and the outdoors is predicted by a semi-empirical model. The relative humidity of the air in the house below is permitted to vary during the winter and is calculated from a moisture balance of the whole building with the indoor moisture production rate and envelope air tightness used as inputs.

The above mathematical model was used to simulate the moisture performance of a new current practice site-built prototype house located in three different climates [cold(heating), mixed, and cooling (hot and humid)] and constructed in compliance with the recommendations for 15 different possible roof designs set forth in the *U.S. DOE Moisture Control Handbook* (Lstiburek and Carmody 1991). The different roof designs included both typical open attic designs and cathedral ceilings. Most of the roofs were ventilated (vent openings were installed in the roof cavity consistent with the 1/300 rule[1]), but a few were not. Most, but not all, had an interior vapor retarder installed in the ceiling construction. These roof constructions were intended to be the best designs to minimize moisture accumulation, thereby preventing material degradation, mold and mildew growth, and loss in thermal performance. But prior to this study, their moisture performance had not been checked with a moisture model.

One purpose of this modeling project was to determine if high moisture content conditions conducive to the growth of decay fungi existed with any of the proposed roof designs. Thus the moisture content of the various roof construction wood members was investigated as a function of time of year for all climates. Focus was on the north-facing plywood roof sheathing because it typically was either the most moist or very close to the most moist of all the various roof wood members. In addition, the relative humidity at the surface between the bottom of the insulation and the top of the polyethylene vapor retarder below it (or the gypsum board when no vapor retarder was in place) was investigated. This was done to determine if mold and mildew would grow at that location, especially in cooling (hot and humid) climates.

The analysis revealed that all the 15 recommended roof constructions performed satisfactorily from a moisture content point of view in that none of the wood members came close to exceeding the fiber saturation level required for the growth of decay fungi. However, a parametric sensitivity analysis is underway that possibly could change that finding, especially for unventilated roofs in the cold (heating) or mixed climates or for homes with high moisture production.

Some of the roof constructions with a ceiling vapor retarder in each climate were found to give rise to surface relative humidities at the top of the vapor retarder during the summer that exceeded the critical 80 percent level believed to be required for mold and mildew growth. That was true for one roof with only rigid insulation in the cold (heating) climate and all the roofs with vapor retarders in both the mixed and cooling (hot and humid) climates. During the summer, the roof ventilation allowed moisture from the outdoor environment to enter the roof cavity where it then diffused inwardly into the construction. Upon reaching the interior vapor retarder, which was cooled by the air conditioned indoor air, its migration was slowed and moisture accumulated, thereby causing the surface relative humidity to rise above the critical 80 percent level.

The simulation results also showed that removing the vapor retarder from the mixed and cooling (hot and humid) climate roofs eliminated the mold and mildew condition. Removing the attic ventilation in those climates also avoided the problem, but that led to plywood moisture contents close to fiber

[1] The 1/300 rule specifies that 1 m^2 (ft^2) of ventilation shall be provided for each 300 m^2 (ft^2) of ceiling area.

saturation in the mixed climate, but not in the cooling (hot and humid) climate. Designing without ventilation and a vapor retarder in the cooling (hot and humid) climate provided the best moisture performance. Without eliminating the use of a vapor retarder or attic ventilation, two of the four mixed climate roofs and four of the six cooling (hot and humid) climate roof designs would have to be considered unsatisfactory. For the mixed and cooling (hot and humid) climates, the roofs without a vapor retarder were found to perform satisfactorily. For those roofs during both winter and summer periods, moisture passed through the construction and did not significantly accumulate within construction layers.

Incidently, the authors of the *U.S. DOE Moisture Control Handbook* were aware that mold and mildew problems might be caused by the presence of a vapor retarder above the cooling (hot and humid) climate ceilings. So they removed them from the roof constructions in a revised hard bound version of the Handbook (Lstiburek and Carmody 1993). According to the findings of this study, that was a wise decision.

Based on the findings of this computer modeling, it is recommended that a vapor retarder ***not*** be installed in residential roofs in mixed or cooling (hot and humid) climates. Moreover, it is recommended that roofs in cooling (hot and humid) climates ***not*** be ventilated.

Details of the model are presented along with particulars of the analysis of the moisture performance of the 15 roof designs in the three climate zones. Furthermore, recommendations for further study are presented.

INTRODUCTION

During the winter, moisture released by occupant activities causes the absolute humidity (or water vapor pressure) inside a house to be higher than that of the outdoor air. This vapor pressure driving force causes water vapor to diffuse through the ceiling construction into the roof cavity. In addition, a buoyant force (i.e., stack effect) is exerted on the indoor air. This causes air flow from the house into the roof/attic through cracks and penetrations in the ceiling construction (e.g., ceiling light fixtures, plumbing vents, joints or cracks above interior partition walls, and HVAC penetrations). That air flow carries moisture with it in the form of water vapor. A portion of this moisture is removed directly by attic ventilation. The remainder is adsorbed or condenses onto the cold interior surfaces of the roof cavity (most important of which is the plywood roof sheathing).

Harrje et al. (1986) measured the seasonal variations in wood moisture content in two New Jersey attics. They observed that the moisture content of the roof sheathing increased during cold winter periods and subsequently decreased during warm summer periods. Similar seasonal variations in the moisture content of roof construction layers were measured by Cleary et al. (1984) in a milder northern California climate. Such variations also were predicted for manufactured housing by Burch (1995) using the original MOIST model (Burch and Thomas 1992). Burch, Tsongas, and Walton (1996) also have predicted the moisture performance of roof constructions of manufactured housing using an improved version of the MOIST model for roof/attic simulations.

It is possible for the moisture content of the roof sheathing to rise above the so-called fiber saturation level, thereby posing a potential for material degradation (e.g., plywood delamination or wood decay) and shortened service life. For wood decay to occur, the wood must have a moisture content above the fiber saturation point (e.g., 28 percent moisture content for plywood) and the wood must be warm (above 10°C [50°F] and optimally between 24°C [75°F] and 33°C [90°F])(Sherwood 1994). It has been presumed that the possibility of roof decay tends to be greater in houses with high indoor relative humidity and substantial ceiling air leakage.

In addition to the concern about material degradation, there also is a concern about the growth of mold and mildew, especially because of the widening recognition of possible adverse health effects (Olson et al. 1993). This is of particular concern during the summer in cooling (hot and humid) climates when warm, moist outdoor air infiltrates into an attic and contacts a cool surface such as a ceiling. When a vapor retarder is installed just above the ceiling, moisture accumulates at its top surface. The surface relative humidity may approach a saturated state, thereby providing a conducive environment for mold and mildew growth. Characteristic pink and chartreuse splotches can develop on the top side of the vapor retarder. In addition, mold and mildew colonies emit fungal spores which may cause an indoor air quality problem (e.g., musty odor) and health-related problems (e.g., allergic responses and/or respiratory illness)(Olson et al. 1993). Mold and mildew problems in cooling (hot and humid) climates have been documented in field studies by Lstiburek (1992a, 1992b). High relative humidities behind interior vapor retarders during the summer in cooling (hot and humid) climates also have been predicted by computer analysis (Burch 1993). It may be that moisture control measures that are designed for winter conditions, such as a ceiling vapor diffusion retarder or roof cavity ventilation, may actually be counterproductive during the summer when used in a cooling (hot and humid) climate, or even in a mixed climate.

In an effort to prevent roof cavity moisture problems, open attics and cathedral ceilings in site-built homes are typically passively ventilated according to the "1/300" rule as mandated by most building codes. That rule specifies that there shall be one square foot (or square meter) of net free ventilation area from roof vents per 300 square feet (or square meter) of ceiling area. That ceiling area can be either the flat ceiling area for open attics or the sloped ceiling area for cathedral ceilings.

Furthermore, a 57 ng/s·m^2·Pa (1 perm) vapor retarder is often used or required to minimize the transport of moisture by diffusion into the roof cavity, especially in cold climates. In mixed and cooling (hot and humid) climates that retarder is generally not used or required by code. It is generally felt that the retarder is not necessary since in the milder climates elevated moisture levels in the winter typically are a not a problem. Moreover, architects, builders and designers usually believe that it is best to let the ceiling "breath."

For manufactured homes the Department of Housing and Urban Development (HUD) issued rules in their Manufactured Home Construction and Safety Standards (U.S. Department of Housing and Urban Development 1994). The rules require manufactured houses to have an interior ceiling vapor retarder, except for houses constructed in the southeastern part of the United States. In addition, manufactured houses constructed with moisture absorbing roof sheathing are required to be provided with either a passive or mechanical ventilation system for removing moisture from their roof cavities. Passive ventilation systems shall have a net free ventilation opening of 1/300 of the attic floor. Mechanical ventilation systems shall provide a minimum air change rate of 0.00010 m^3/s per m^2 (0.02 ft^3/min per ft^2) of attic floor area. Single-wide houses constructed with metal roofs are not required to have attic ventilation.

As noted above, providing an interior vapor retarder in the ceiling construction and ventilating the roof cavity may be counterproductive and actually cause a summer moisture problem in site-built or manufactured housing located in hot and humid climates. This is because the ventilation air flow can transport a large amount of moisture into the roof cavity from outdoors. It is subsequently absorbed at the upper surface of the ceiling insulation, where it readily diffuses to the upper surface of the vapor retarder which may be cooled by the indoor air conditioning equipment below the dew point temperature of the roof cavity air. In this situation, condensation occurs and the relative humidity at the upper surface of the vapor retarder approaches a saturated state, thereby providing a conducive environment for mold and mildew growth. A monthly mean surface relative humidity of greater than 80 percent is required for the growth of mold and mildew (International Energy Agency 1990). Fungal spores may enter the living space and cause indoor air quality and health-related problems (Olson et al. 1993).

In terms of previous mathematical analyses of roof moisture performance, a transient heat and moisture transfer model developed at the National Institute of Standards and Technology (NIST) and called MOIST (Burch and Thomas 1992) was used to analyze the effectiveness of various moisture control practices for roof cavities of manufactured housing. In that study (Burch 1995), it was found that a combination of passive measures consisting of a ceiling vapor retarder, sealing air leakage sites in the ceiling construction, and providing attic ventilation openings maintained the moisture content of the roof sheathing well below fiber saturation.

However, the version (2.1) of the MOIST model used in that study had several important limitations that likely influenced the results. First, the model itself was intended to analyze only walls or flat roofs. In fact, its main application was towards assessment of wall moisture performance. Second, the indoor relative humidity in the house below had to be held constant during the simulation. In actual houses, the indoor relative humidity varies considerably throughout the year, and that can influence moisture results substantially; thus simulation results with a floating indoor relative humidity are quite different (Tsongas, et al. 1995). Third, the stack effect air flow from the house into the roof cavity was treated as constant. In practice, this air flow will tend also to vary as a function of time of year. And third, the attic ventilation rate was taken to be constant during the simulation. Yet it is known to vary considerably with wind speed.

Because of those restrictions in the MOIST model, it was decided to modify the model to remove those limitations and improve the versatility of the model. Since the time of that first NIST roof modeling study, the MOIST model has been substantially modified and improved in scope. All of the above-noted restrictions have been removed. In fact, an essentially new computer model has been developed specifically to analyze the moisture performance of both open attic and cathedral ceiling type roofs, rather than just flat roofs. In the present study, that more comprehensive model is presented. Of major importance is the fact that it does away with all the limitations of the previous model mentioned earlier. This new, improved model is subsequently used to simulate the performance of a current practice site-built prototype house. In this and a more detailed follow up parametric sensitivity analysis study, several factors that affect the moisture performance of roofs of site-built homes are analyzed. The effectiveness of the current moisture control practice of using passive roof ventilation as specified in the building codes is investigated in cold (heating), mixed, and cooling (hot and humid) climates. The moisture performance of roofs of manufactured houses, as assessed using the new model, is the subject of a concurrent study (Burch, Tsongas, and Walton 1996) sponsored by HUD.

For this report, the new model is used to assess the moisture performance of the 15 roof constructions recommended in the *U.S. DOE Moisture Control Handbook* (Lstiburek and Carmody 1991). The handbook was prepared to provide guidance to architects and building designers regarding the moisture performance of residential building components. The handbook recommends roof, wall, and foundation constructions for three different climatic regions of the United States (the so-called cold [heating], mixed, and cooling [hot and humid] climates). The constructions were intended to be designs that would minimize moisture accumulation, thereby preventing degradation of materials, mold and mildew growth, and loss of thermal performance. The selection of roofs for the handbook was achieved through consensus of a panel of experts from government and industry. In some cases, roof constructions were included in the handbook for which a minority of the panel had concerns regarding their moisture performance. However, at the time the handbook was prepared, there was no readily available computer model to assess the moisture performance of the proposed roof designs. Thus it was decided to use the new MOIST Attic Model to do so as one of its first major applications. Details of the application of the model will be described after the model itself is first described.

COMPUTER MODEL THEORY

The computer model theory was originally presented in Burch, Tsongas, and Walton (1996) and is presented again for the convenience of the reader.

Assumptions

Some of the more important assumptions of the new roof moisture and heat transfer model are given below:

- Moisture and heat transfer are one-dimensional;
- Air within the ventilated cavity is well mixed; and
- The wetting of exterior surfaces by rain is neglected, and the insulating effect and change in roof solar absorptance from a snow load are neglected.

Other assumptions are discussed in the model presentation below.

Basic Transport Equations

The basic transport equations and their solution are taken from Pedersen[2] (1990). Pedersen's approach was utilized rather than that in previous MOIST algorithms because it is computationally more efficient and more accurate. The transport equations are briefly presented below.

Within each material of the construction, the moisture distribution is governed by the following conservation of mass equation:

$$\frac{\partial}{\partial y}\left(\mu\frac{\partial p_v}{\partial y}\right) - \frac{\partial}{\partial y}\left(K\frac{\partial p_l}{\partial y}\right) = \rho_d\frac{\partial \gamma}{\partial t} \qquad (1)$$

The first term on the left side of Equation 1 represents water vapor diffusion, whereas the second term represents capillary transfer. The right side of Equation 1 represents moisture storage within the material. The minus sign accounts for the fact that liquid flows in a porous material in the same direction as the gradient in capillary pressure. The potential for transporting water vapor is the vapor pressure (p_v) with the permeability (μ) serving as the transport coefficient. The potential for transferring liquid water is the capillary pressure (p_l) with the hydraulic conductivity (K) serving as the transport coefficient. Other symbols contained in the above equation include the dry density of the material (ρ_d), moisture content (γ), distance (y), and time (t). All symbols are defined in the Nomenclature section at the end of this report. The sorption isotherm (i.e., the relationship between equilibrium moisture content and moisture content) and the capillary pressure curve (i.e., the relationship between capillary pressure and moisture content) were used as constitutive relations in solving Equation 1.

The temperature distribution is calculated from the following conservation of energy equation:

$$\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + h_{lv}\frac{\partial}{\partial y}\left(\mu\frac{\partial p_v}{\partial y}\right) = \rho_d c\frac{\partial T}{\partial t} \qquad (2)$$

The first term on the left side of Equation 2 represents heat conduction, whereas the second term is the latent heat transfer derived from any phase change associated with the movement of moisture. The right side of Equation 2 represents the storage of heat within a material. Symbols in the above equation include temperature (T), specific heat (c), and latent heat of vaporization (h_{lv}).

In Equation 1, the water vapor permeability and the hydraulic conductivity are strong functions of moisture content. In Equation 2, the thermal conductivity is a weaker function of moisture content. The effect of moisture on thermal conductivity has been measured for only a few building materials. For the present analysis, the thermal conductivity is assumed to be constant.

---

[2] Carsten Pedersen recently changed his name to Carsten Rode.

Ventilated Cavity Moisture and Heat Balance

Applying the principle of conservation of mass to a ventilated cavity, the sum of the evaporation rates from the ventilated cavity surfaces plus the rate of moisture transfer by air flow from the house into the cavity is equal to the rate of moisture removed by outdoor ventilation:

$$\sum_{n=1}^{N} A_n m_n (p_{vs,n} - p_{v,c}) + \rho_a \dot{V}_{h\rightarrow c}(\omega_i - \omega_c) = \rho_a \dot{V}_{c\rightarrow o}(\omega_c - \omega_o) \tag{3}$$

where

A_n = area of surface n, m^2 (ft^2)
m_n = mass transfer coefficient, $kg/s{\cdot}m^2{\cdot}Pa$ ($lb/h{\cdot}ft^2{\cdot}inHg$)
$p_{vs,n}$ = vapor pressure at surface n, Pa (inHg)
$p_{v,c}$ = vapor pressure of the cavity air, Pa (inHg)
$\dot{V}_{h\rightarrow c}$ = volumetric air flow rate from house into the attic, m^3/s (ft^3/min)
ω_i = humidity ratio of indoor air
ω_c = humidity ratio of cavity (attic) air
ω_o = humidity ratio of outdoor air
$\dot{V}_{c\rightarrow o}$ = ventilation air flow rate from cavity to outdoors (attic), m^3/s (ft^3/min)

The other symbols have previously been defined.

In a similar fashion, the principal of conservation of energy may be applied to the cavity air volume. The net rate of convective heat transfer from the cavity surfaces plus the rate of energy transfer by air flow from the house into the cavity is equal to the rate of energy removed by outdoor ventilation:

$$\sum_{n=1}^{N} A_n h_{c,n} (T_{s,n} - T_c) + \rho_a c \dot{V}_{h\rightarrow c}(T_i - T_c) = \rho_a c \dot{V}_{c\rightarrow o}(T_c - T_o) \tag{4}$$

where

$h_{c,n}$ = convective heat transfer coefficient at surface n, $W/m^2{\cdot}K$ ($Btu/h{\cdot}ft^2{\cdot}°F$)
$T_{s,n}$ = temperature at surface n, °C (°F)
T_c = temperature of cavity (attic) air, °C (°F)
T_o = temperature of outdoor air, °C (°F)

The other symbols have been previously defined. Radiation exchange among the ventilated cavity surfaces is handled using the mean-radiant-temperature network method described by Carrol (1980).

Air Flow from House into Attic

The air flow rate ($\dot{V}_{h\rightarrow c}$) from the house into the cavity is predicted using the equation:

$$\dot{V}_{h\rightarrow c} = L_e \sqrt{\frac{2\Delta p_r}{\rho_a}} \left(\frac{\Delta p_t}{\Delta p_r} \right)^{0.65} \tag{5}$$

In the above equation, Δp_t refers to the total stack effect pressure, and Δp_r is a reference pressure of 4 Pa (0.016 in H_2O).

Air flow passes through the following three leakage areas: the ceiling (L_c) , the roof (L_r) , and the house below (L_w). The effective leakage area for stack effect air flow of the series combination (L_e) of the three areas is given by the relation:

$$L_e = \left[\left(\frac{1}{L_w} \right)^{1/0.65} + \left(\frac{1}{L_c} \right)^{1/0.65} + \left(\frac{1}{L_r} \right)^{1/0.65} \right]^{-0.65} \tag{6}$$

Here the effective leakage area (L_i or ELA_i) for each of the house parts has been aggregated at a single location placed at the mid-height level of each part. The total stack effect pressure head (Δp_t) is equal to the sum of the pressures for the house and the roof cavity, or:

$$\Delta p_t = \rho_a H_h \left(\frac{T_i - T_o}{T_o} \right) + \rho_a H_c \left(\frac{T_c - T_o}{T_o} \right) \tag{7}$$

The first and second terms are the house and roof cavity stack effect pressures, respectively (ASHRAE 1993). The symbols H_h and H_c refer to the stack height for the house and the cavity (attic), respectively.

The NIST Contaminant Air Flow Model (Walton 1994) was used to investigate the effect of the assumption of aggregating the wall effective leakage area (ELA) at a single location at the mid-height level. For the investigation, the stack-effect air flow from the house into the roof cavity was predicted for two cases. In the first case, the wall ELA was equally distributed into eight separate ELA's spaced at equal intervals from the floor to the ceiling. In the second case, the wall ELA was aggregated at a single location at the mid-height level. The two simulations agreed within 9 percent, thereby indicating the simplifying assumption was reasonable.

Cavity Ventilation Rate

The single-zone infiltration model (the so-called "LBL model") developed by Sherman and Grimsrud (1980) was applied to estimate the volumetric air exchange rate ($\dot{V}_{c\rightarrow o}$) between a roof cavity and the outdoor environment:

$$\dot{V}_{c \to o} = L_r \left[C_{\Delta T,c} |T_c - T_o| + C_{v,c} v^2 \right]^{0.5} \tag{8}$$

Here the driving forces for air exchange are the absolute temperature difference between the cavity (attic) and outdoor air (T_c - T_o) and the wind speed (v). The coefficients ($C_{\Delta T,c}$ and $C_{v,c}$) are empirical coefficients evaluated by fitting the above equation to a set of measured data, as described in a later section.

Indoor Boundary Conditions

At the indoor surface of the construction, the moisture transfer through an air film and paint layer (or wallpaper) is equated to the diffusion transfer into the solid material surface:

$$M_{e,i}(p_{v,i} - p_v) = -\mu \frac{\partial p_v}{\partial y} \tag{9}$$

where the quantities are evaluated at the indoor surface. Here, an effective permeance ($M_{e,i}$), defined by:

$$M_{e,i} = \frac{1}{\frac{1}{M_{f,i}} + \frac{1}{M_{p,i}}} \tag{10}$$

has been introduced. The effect of a thin paint layer is taken into account as a surface conductance ($M_{p,i}$) in series with the convective mass transfer coefficient ($M_{f,i}$) for the air film.

At the same boundary, the heat transferred through the air film, ignoring the thermal resistance of the paint layer, is equated to the heat conducted into the indoor surface:

$$(h_{r,i} + h_{c,i})(T_i - T) = -k \frac{\partial T}{\partial y} \tag{11}$$

where all quantities are evaluated at the indoor surface. The symbols $h_{r,i}$ and $h_{c,i}$ are the radiative and convective heat transfer coefficients, respectively. The symbol k is the thermal conductivity of the surface material.

Outdoor Boundary Conditions

At the outdoor surface of the construction, a set of equations similar to Equations 9-10 were applied to compute the moisture transfer. The heat conducted into the outdoor surface and the absorbed solar radiation is set equal to the heat loss from the roof to the outdoor air plus the radiation exchange between the roof and the sky:

$$-k\frac{\partial T}{\partial y} + \alpha H_{sol} = h_{c,o}(T - T_o) + h_{r,o}(T - T_{sky}) \tag{12}$$

where all quantities are evaluated at the outdoor surface. The symbol α is the solar absorptance of the exterior surface, and H_{sol} is the incident solar radiation. The coefficient $h_{c,o}$ is the convective heat transfer coefficient at the outdoor surface, and $h_{r,o}$ is the radiative heat transfer coefficient defined by the relation:

$$h_{r,o} = 4E\sigma T_m^3 \tag{13}$$

where E is the emittance factor which includes the surface emissivity and the view factor from the outdoor surface to the sky and T_m is the mean temperature between the surface and the sky. The solar radiation incident onto exterior surfaces having arbitrary tilt and orientation was predicted using algorithms given in Duffie and Beckman (1991). The sky temperature (T_{sky}) was calculated using an equation developed by Bliss (1961).

Indoor Temperature and Humidity Conditions

Space Heating Operation. When the daily average outdoor temperature is less than or equal to the balance point temperature for space heating, the house operates in a space heating mode. The indoor temperature is taken to be equal to the heating set point temperature. The indoor relative humidity is permitted to vary and is calculated from a moisture balance of the whole building.

The rate of moisture production ($\dot{W}$) by the occupants is equal to the rate of moisture removed by natural and/or forced ventilation plus the rate of moisture storage at interior surfaces and furnishings:

$$\dot{W} = \rho_a \dot{V}_{h,t}(\omega_i - \omega_o) + \kappa A_f(\phi_i - \phi_{i,\tau}) \tag{14}$$

where

$\dot{V}_{h,t}$ = total volumetric ventilation rate for the house, m^3/s (ft^3/min)
A_f = floor area of the house, m^2 (ft^2)
ϕ_i = indoor relative humidity

The sorption constant per unit floor area (κ) must be determined from a whole house experiment (see TenWolde 1994). However, in a previous study of wall moisture performance (Tsongas et al. 1995), we found that considerable variations in its value had essentially no effect on the wall moisture accumulation. Using the psychrometric relationship between humidity ratio (ω) and relative humidity (ϕ) as a constitutive relation, the above equation may be solved for the indoor relative humidity (ϕ_i).

The hygric memory ($\phi_{i,\tau}$) is computed from the relation:

$$\phi_{i,\tau} = \frac{\sum_{n=N-4\tau}^{N-1} Z(n)\phi_i(n)}{\sum_{n=N-4\tau}^{N-1} Z(n)} \tag{15}$$

The exponential weighting factors Z(n) are defined as:

$$Z(n) = e^{-(N-n)/\tau} \tag{16}$$

In the hourly calculations, the dew point temperature of the indoor air is compared with the temperature of the inside glass surface to determine if condensation occurs. When condensation occurs, the vapor pressure of the indoor air is taken to be equal to the saturation pressure at the inside glass surface. The indoor relative humidity is calculated from the indoor temperature and vapor pressure using psychrometric relationships.

The natural ventilation rate for the house is predicted by the single-zone Lawrence Berkeley Laboratory (LBL) Infiltration Model developed by Sherman and Grimsrud (1980) and described by ASHRAE (1993), which is given by:

$$\dot{V}_{h,n} = L_h \left[C_{\Delta T,h}|T_i - T_o| + C_{v,h}v^2\right]^{0.5} \tag{17}$$

Here the driving forces for air exchange are the absolute temperature difference between the indoor and outdoor air (T_i - T_o) and the wind speed (v). When mechanical ventilation ($\dot{V}_{h,m}$) is present, the total ventilation rate $\dot{V}_{h,t}$ in Equation (14) is determined by the relation (Palmiter and Bond 1991):

$$\begin{aligned} &\text{If } \dot{V}_{h,m} < 2\dot{V}_{h,n}, \quad \dot{V}_{h,t} = \dot{V}_{h,n} + 0.5\,\dot{V}_{h,m} \\ &\text{If } \dot{V}_{h,m} \geq 2\dot{V}_{h,n}, \quad \dot{V}_{h,t} = \dot{V}_{h,m} \end{aligned} \tag{18}$$

It should be noted that in Equation 18, $\dot{V}_{h,m}$ is the actual mechanical ventilation rate produced by the ventilation equipment installed in the house, as opposed to the rated value. The actual value is typically about half of the rated value (Tsongas 1990).

Space Cooling Operation. When the daily average outdoor temperature is greater than or equal to the balance point temperature for space cooling, the house operates in a space cooling mode. The indoor temperature and relative humidity are maintained at constant specified values. When the space cooling equipment is turned off, it is assumed that the occupants will open the windows, and the building operates with opened windows, as specified below.

Open Window Operation. When the daily average outdoor temperature is greater than the balance point for space heating and less than the balance point for space cooling, then neither space heating nor space cooling are required, and the indoor condition is assumed to float. It is assumed that the windows are opened, and the indoor temperature and relative humidity are equal to the outdoor values.

Solution Procedure

A FORTRAN 77 computer program, called the MOIST Attic Model, was prepared to solve the above system of equations. Finite-difference equations were developed to represent the basic moisture and heat transport equations (Eqs. 1 and 2).

The solution of the complete system of equations proceeded by first solving for all the material temperatures and the cavity air temperature. A flow chart describing the steps of the thermal solution is given in Figure 1. Since the material temperatures and the cavity air temperature are dependent upon one another, it is necessary to iteratively solve at each time step the material temperatures and cavity air temperature until convergence is achieved.

The model next solves for the water vapor pressure distribution within the materials and the cavity vapor pressure. A flow chart describing the steps of the moisture solution is given in Figure 2. The model next solves for the distribution of capillary pressures within the materials. From the predicted gradients in vapor pressure and capillary pressure and the transport coefficients for vapor and liquid flows, a new set of material moisture contents is calculated. The model is now ready to proceed to the next time step. Because the material vapor pressures and the cavity vapor pressure are dependent on one another, it is necessary to iteratively solve at each time step the material vapor pressures and cavity vapor pressure until convergence is attained.

Before making the final computer runs for the present study, a series of special computer runs were carried out to establish that the finite-difference representation of the transport equations was indeed converging. In a sequence of simulations, the number of the finite-difference nodes in each material was doubled until no further change in the solution occurred. The number of finite-difference nodes used in the roof construction, which is the focus of the analysis, is given in Table 1 below.

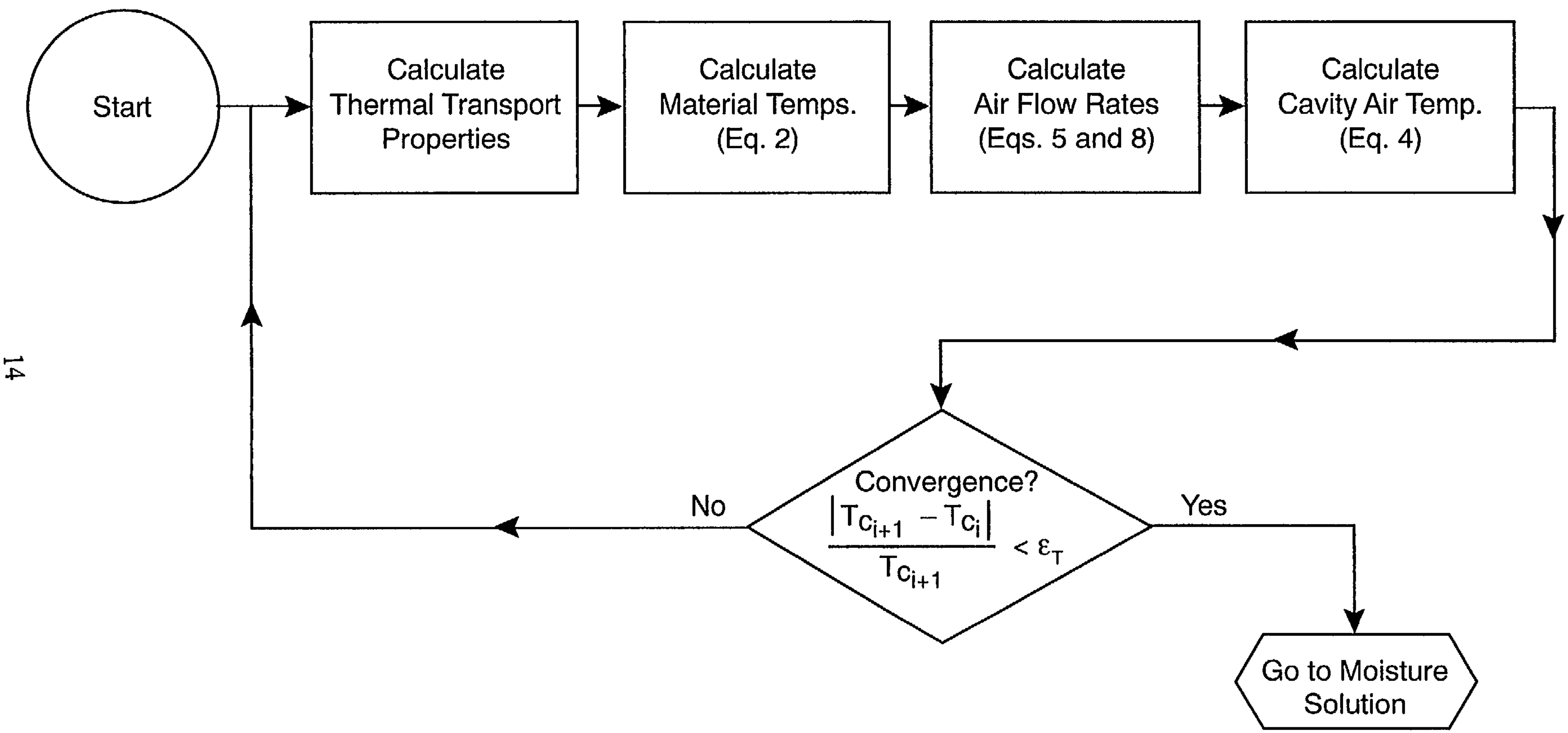


Fig. 1. Flow chart of thermal solution.

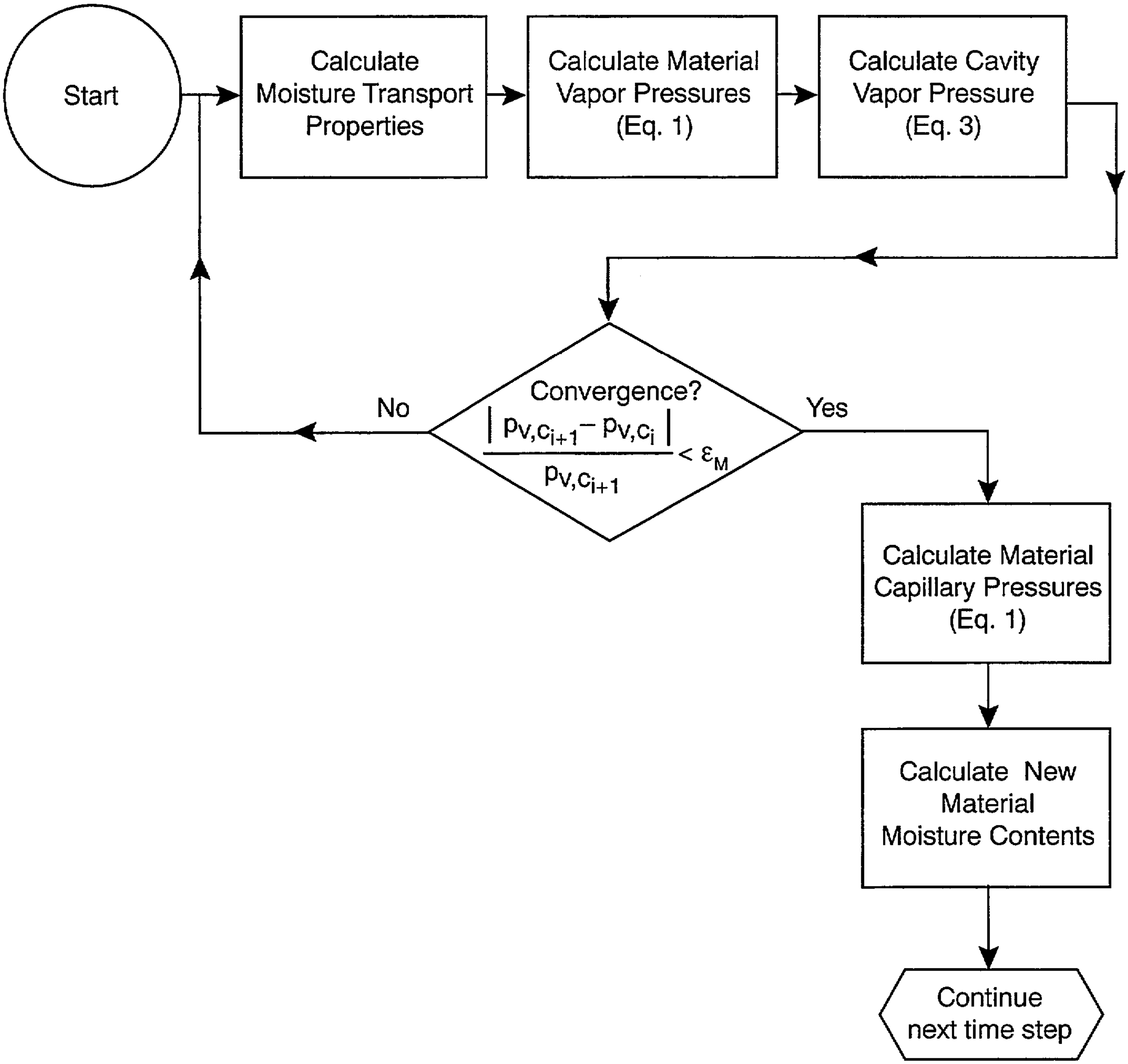


Fig. 2. Flow chart of moisture solution.

Table 1. Number of Finite-Difference Nodes in Roof 1 - Cold (Heating) Climate		
Construction Layer	Thickness, mm (in)	Nodes
Thin Lower Surface Layer, Plywood Roof Sheathing	1.6 (0.063)	2
Remainder Layer, Plywood Roof Sheathing	11.1 (0.438)	5
Building Paper	0.79 (0.031)	2
Asphalt Roof Shingles	6.4 (0.25)	2

A similar number of nodes were used in the other roof constructions. Dividing the plywood into two separate layers (i.e., a thin surface layer and a remainder layer) is a method used to achieve convergence of the mathematical solution with a fewer number of nodes. It also allowed determination of the moisture content of the surface layer of the plywood sheathing adjacent to the cavity; that layer should have the highest moisture content of the sheathing.

In another set of simulations, the convergence criteria for the thermal solution (ϵ_T) and the convergence criteria for the moisture solution (ϵ_M) were decreased until no further change in the solution occurred. A value of 1.0 X 10^{-4} for ϵ_m and ϵ_T provided convergence of the mathematical solution.

DESCRIPTION OF CURRENT PRACTICE HOUSE AND ROOF CONSTRUCTIONS

House and Roof Construction Characteristics

The current practice house simulated in this study is a single story site-built house having a floor area of 139.4 m^2 (1500 ft^2) and either a 2.44 m (8 ft) flat ceiling height or an average 3.38 m (11.1 ft) cathedral ceiling height. The house length is 15.2 m (50 ft) long by 9.1 m (30 ft) wide. The moisture performance of 15 different roof constructions presented in the *U.S. DOE Moisture Control Handbook* (Lstiburek and Carmody 1991) was analyzed. There are nine open-type conventional attic constructions with flat ceilings (hereafter referred to as "open attics") and six cathedral ceilings.

Of the 15 roof constructions, five are located in a cold (heating) climate (Madison, WI), four are located in a mixed climate (Washington, D.C.), and six are located in a cooling climate (also referred to as a hot and humid climate) (Lake Charles, LA). A summary of the different types and their locations is given in Table 2 below. The designations for each of the 15 roofs are given (e.g., HCR1 for cold (heating) climate roof number 1) along with the number (in parentheses) of each type in each climate.

Table 2. Roof Construction and Climate Location Summary		
Roof Climate Location	Open Attic Type	Cathedral Ceiling
Cold (Heating) Climate (Madison, WI)	HCR1 (1)	HCR2-5 (4)
Mixed Climate (Washington, D.C.)	MCR1-2 (2)	MCR3-4 (2)
Cooling (Hot and Humid) Climate (Lake Charles, LA)	CCR1-4 (4)	CC5-6 (2)

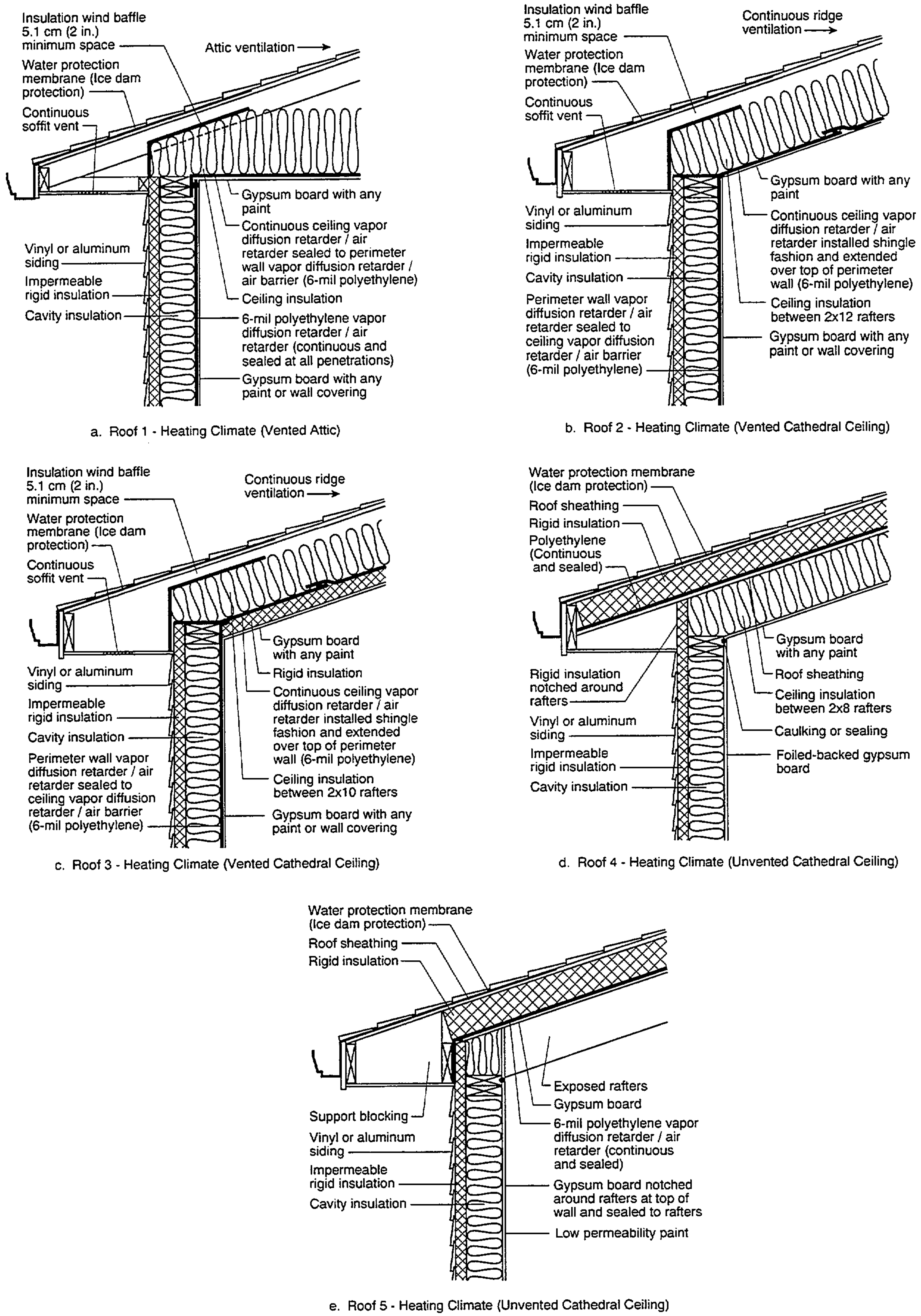
A cross section of each roof construction for each of the three climates is shown in Figures 3, 4, and 5. The sloping roofs face north and south; the gable end walls face east and west. The slope of the roof is 22.6° corresponding to a 5 in 12 pitch. The gable end walls are constructed of 0.95 cm (3/8 in.) asphalt-impregnated fiberboard and vinyl siding. All of the roofs are assumed to have medium-colored asphalt shingles with a total thickness of 0.64 cm (0.25 in.) and a solar absorptance of 0.8 (the average absorptance of 34 samples of different colors ranging from white to black [Parker et al. 1993]).

The construction of the exterior portion of all the roofs is comprised of 1.27 cm (0.5 in.) exterior-grade plywood, asphalt roofing paper, and asphalt shingles. The ceiling construction (or bottom of the roof cavity) consists of 1.27 cm (0.5 in.) gypsum board with 689 ng/s·m^2·Pa (12.0 perm) latex paint applied to its interior surface, except for mixed climate roof 4 (MCR4) that has impermeable paint (57 ng/s·m^2·Pa [1.0 perm]). If a vapor retarder is present, it is 0.015 cm (6 mil) polyethylene ("poly"). In the roof and ceiling construction, the framing members (including trusses) are spaced 0.61 m (24 in.) on center.

The insulation levels in the roof constructions are those required by local code in the three climate locations; they are given in Table 3 below. Common sizes of dense fiberglass batts were assumed so the insulation would fit within the smallest rafter height, as per typical construction practice. Depending on the total R-value, the different insulation batts had slightly different R-values per inch.

Based on the results of a wall moisture performance study using the same indoor moisture balance model (Tsongas et al. 1995), it was decided to assume a relatively airtight house. That was done since the intent of the analysis was to look at fairly worst case conditions to see how the roof constructions would perform from a moisture point of view. An overall whole house effective leakage area (ELA) of 355 cm^2 (55 in.^{2}) was assumed for all roof cases, which corresponds to a natural air change rate of about 0.25 ach (air changes per hour). That is tight, but not overly so.

Based on airtightness test results of the five tightest homes in a total sample of 20 Canadian site-built houses (Buchan, Lawton, Parent, Ltd 1991), the authors assumed that the ceiling ELA is 55 percent of the whole house total, or 194 cm^2 (30 in.^{2}). Neither the whole house or the ceiling ELA values were varied for this report, although such variation is planned for the more detailed parametric



a. Roof 1 - Heating Climate (Vented Attic)

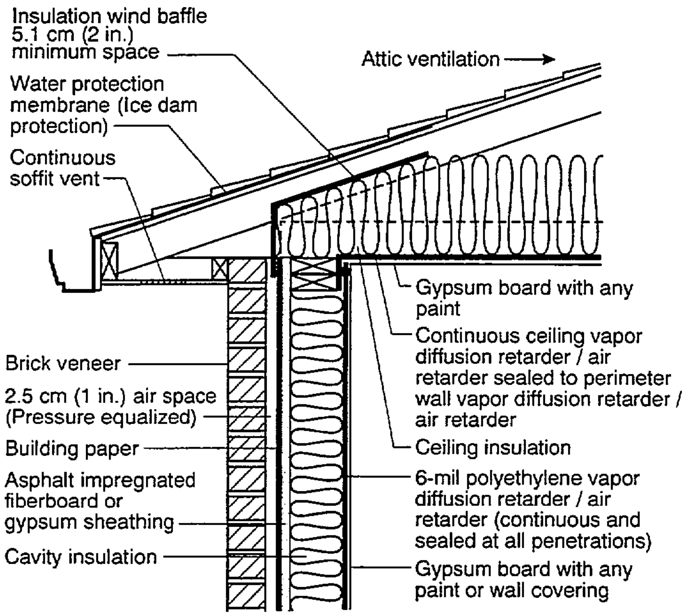
b. Roof 2 - Heating Climate (Vented Cathedral Ceiling)

c. Roof 3 - Heating Climate (Vented Cathedral Ceiling)

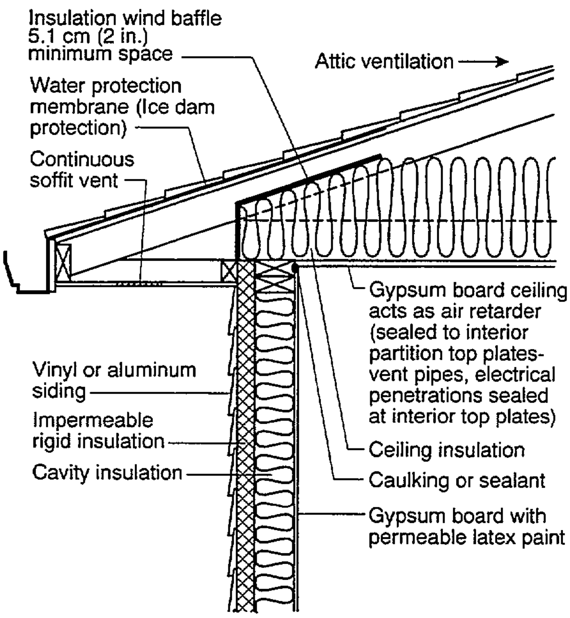
d. Roof 4 - Heating Climate (Unvented Cathedral Ceiling)

e. Roof 5 - Heating Climate (Unvented Cathedral Ceiling)

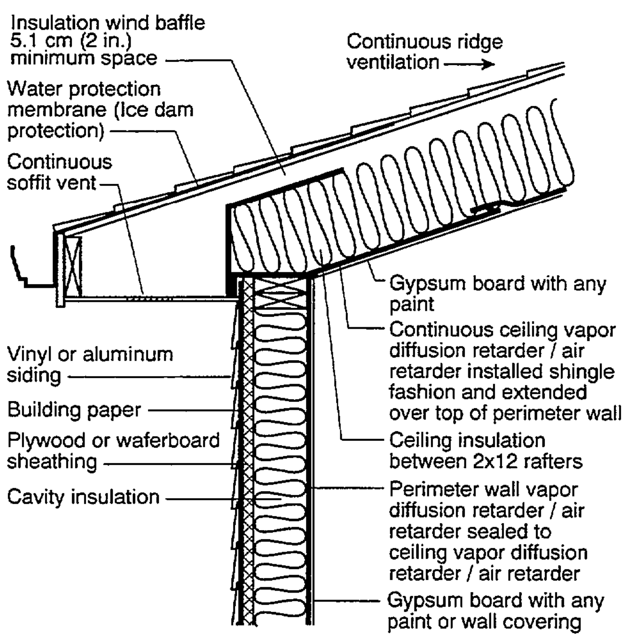
Fig. 3. Half cross sections of cold (heating) climate roof constructions.



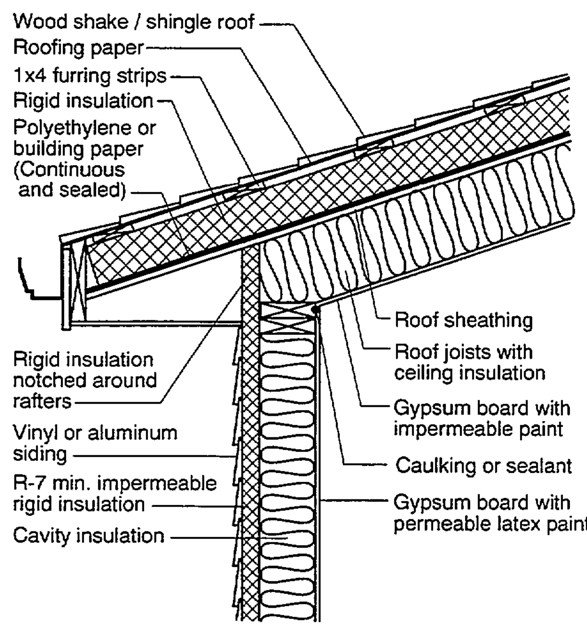
a. Roof 1 - Mixed Climate (Vented Attic)



b. Roof 2 - Mixed Climate (Vented Attic)

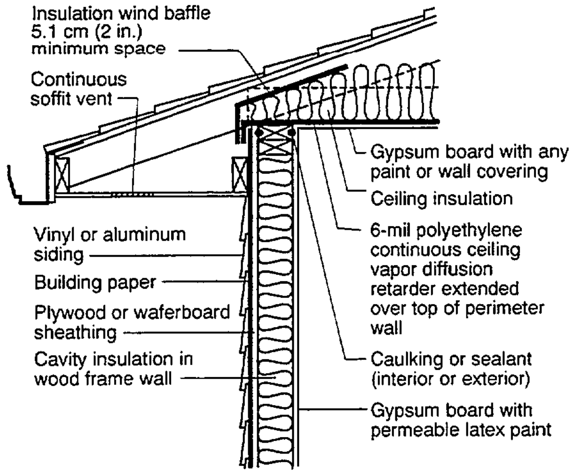


c. Roof 3 - Mixed Climate (Vented Cathedral Ceiling)

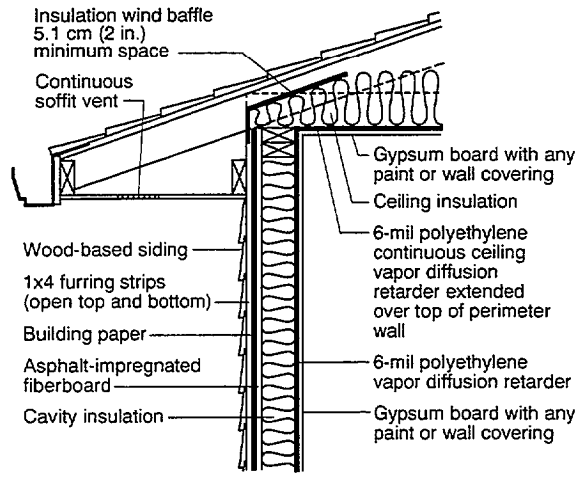


d. Roof 4 - Mixed Climate (Unvented Cathedral Ceiling)

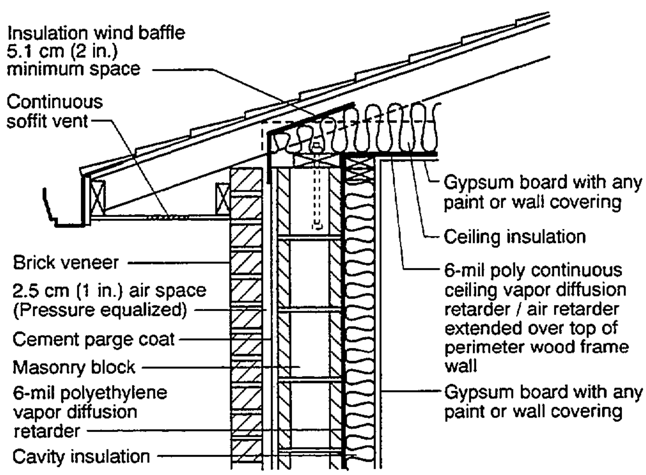
Fig. 4. Half cross sections of mixed climate roof constructions.



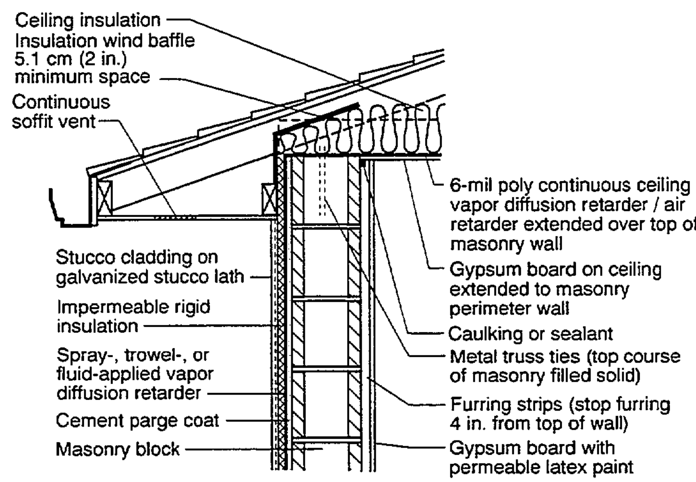
a. Roof 1 - Cooling Climate (Vented Attic)



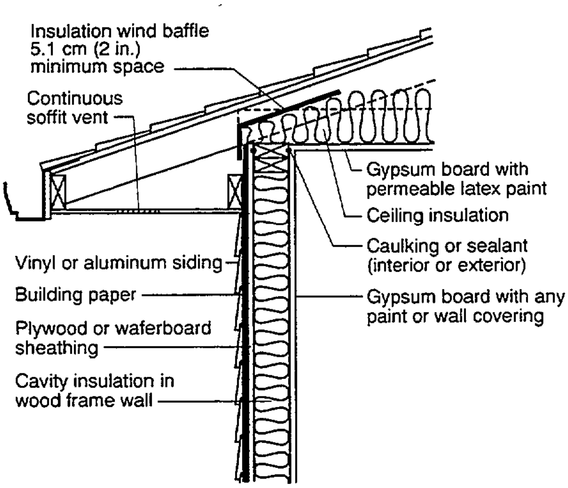
b. Roof 2 - Cooling Climate (Vented Attic)



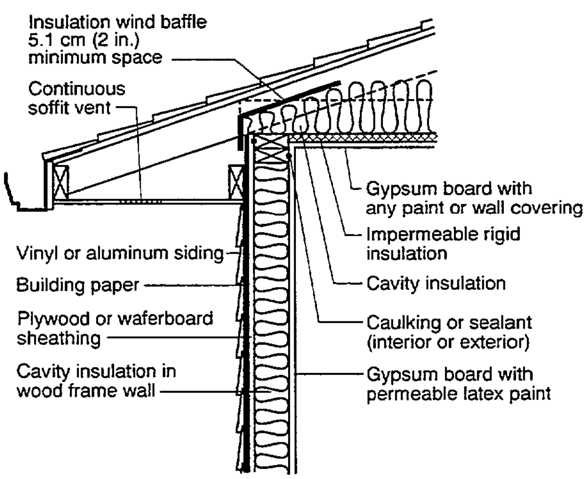
c. Roof 3 - Cooling Climate (Vented Attic)



d. Roof 4 - Cooling Climate (Vented Attic)



e. Roof 5 - Cooling Climate (Vented Attic)



f. Roof 6 - Cooling Climate (Vented Attic)

Fig. 5. Half cross sections of cooling (hot and humid) climate roof constructions.

Table 3. Roof Insulation R-Value Summary		
Roof Climate Location	Open Attic Type	Cathedral Ceiling
Cold (Heating) Climate (Madison, WI)	6.69* (38)**	6.69* (38)**
Mixed Climate (Washington, D.C.)	5.28 (30)	5.28 (30)
Cooling (Hot and Humid) Climate (Lake Charles, LA)	5.28 (30)	5.28 (30)

* Thermal resistance units: $m^2 \cdot K/W$
** Thermal resistance units: $ft^2 \cdot h \cdot {}^\circ F/Btu$

sensitivity analyses to be reported in a follow-on study. For ventilated roof cavities the ELA of the house below the ceiling is 45 percent of the whole house total or 161 cm^2 (25 $in.^2$). When relatively air tight roofs were assumed with some of the unventilated cathedral ceiling constructions [i.e., a roof ELA of 6.5 cm^2 (1 $in.^2$)], then the house below ELA was 348 cm^2 (54 $in.^2$). While the same ceiling construction and ELA was assumed for all the roof cases except the one (MCR2) that utilized the airtight drywall sealing approach, it was felt that the unventilated cathedral type roofs would be fairly airtight (asphalt shingles over continuous lapped building paper over plywood sheathing over rigid insulation); hence their low roof ELA.

Consistent with the current roof ventilation code for site-built homes, the roof construction was fitted with roof cavity vents having a net free open area of 1/300 of the ceiling area, or 4,342 cm^2 (673 $in.^2$) for the open attics and 5535 cm^2 (858 $in.^2$) for the ventilated cathedral ceilings (based on the sloped ceiling area). The attic volume for the open attics was simply based on the ceiling area and the peak height for the given roof slope. The roof cavity volume for the ventilated cathedral ceilings assumed a 5.08 cm (2 in.) high air slot above the insulation between each of the rafters, as per the *Moisture Control Handbook* specifications. However, for the unventilated cathedral ceilings, a thin 0.318 cm (0.125 in.) high cavity was assumed between each of the rafters (the model requires the existence of a cavity). No runs were made with mechanical roof ventilation or with mechanical house ventilation in this initial study. The passive roof cavity ventilation rates for the open attic and cathedral type roofs are discussed in a later section.

Weather, Indoor, and Occupant Conditions

In the computer analysis, the hourly outdoor boundary conditions (i.e., ambient temperature, relative humidity, wind speed, and incident solar radiation) were obtained from ASHRAE WYEC weather data (Crow 1981). During the winter when space heating was required, the set point temperature was 20°C (68°F). The occupant activities produced moisture at a rate of 10.9 kg/day (24.0 lb/day), and the indoor relative humidity floated and was predicted from a moisture balance of the whole building. During the summer when space cooling was assumed, the set point temperature and indoor relative humidity were 24°C (76°F) and 56 percent, respectively. Summer air conditioning was assumed because cooling would produce the worst mold and mildew conditions at the insulation-poly/ceiling interface (the most likely location for summer mold and mildew growth).

Six months of additional weather data were used to initialize the reported one year simulation results to reduce the effect of the assumed initial construction layer moisture content and temperature.

PARAMETERS USED IN ANALYSIS AND MATERIAL PROPERTY MEASUREMENTS

Moisture

Sorption Isotherms. For most of the construction materials comprising the current practice house, sorption isotherms were measured in the laboratory at the National Institute of Standards and Technology. A sorption isotherm is the relationship between moisture content and relative humidity at equilibrium for a specific temperature. The sorption isotherms were determined by placing eight small specimens of each material in vessels above saturated salt-in-water solutions. Each saturated salt-in-water solution provided a fixed relative humidity (Greenspan 1977). The vessels were maintained at a temperature of 24°C ± 0.2°C (75°F ± 0.4°F) until the specimens reached a steady-state equilibrium. The equilibrium moisture content was plotted versus relative humidity to give the sorption isotherm. Separate sorption isotherm data were obtained for specimens initially dry (adsorption isotherm) and for specimens initially saturated (desorption isotherm). A detailed description of the measurement method is given in Richards et al. (1992).

Edwards (1996) and Hedlin (1967) have studied the effect of temperature on the sorption isotherm for a few building materials and found the effect to be small. For the present analysis, the effect of temperature on the sorption isotherm was neglected.

The mean of the adsorption and desorption isotherm measurements was fit to an equation of the following form:

$$\gamma = \frac{B_1\phi}{(1+B_2\phi)(1-B_3\phi)} \tag{19}$$

The coefficients B_1, B_2, and B_3 were determined by regression analysis and are summarized in Table 4. The asphalt roof shingles and vinyl siding were treated as vapor impermeable materials, and the storage of moisture in these materials was neglected. A plot of the sorption isotherms of the materials is given in Figure 6.

Permeability Measurements. The water vapor permeability of most of the hygroscopic materials was measured using permeability cups placed in controlled environments. Five circular specimens, 140 mm (5.5 in.) in diameter, of each material were sealed at the top of open-mouth glass cups. The cups were subsequently placed inside sealed glass vessels maintained at a constant temperature. Saturated salt-in-water solutions were used inside the glass cups and surrounding glass vessels to generate a

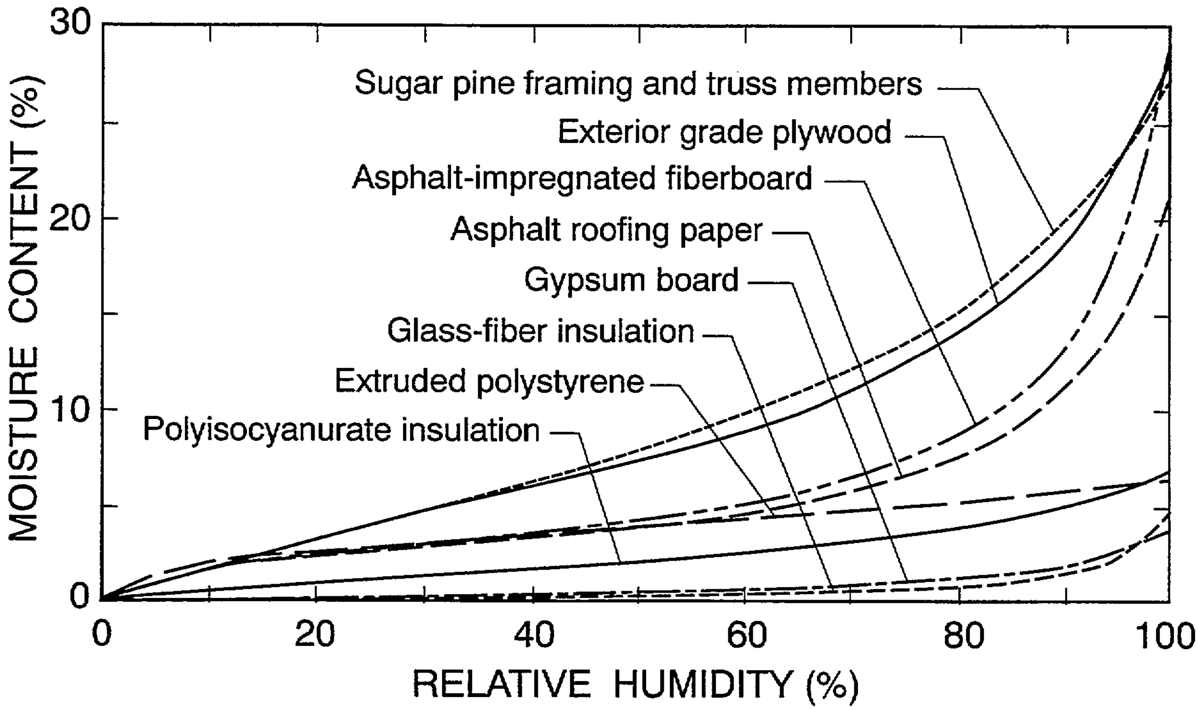


Fig. 6. Sorption isotherms of the materials.

Table 4. Sorption Isotherm Regression Coefficients			
Materials	B_1	B_2	B_3
Exterior-Grade Plywood Sheathing	0.344	6.18	0.828
Framing and Truss Members (Pine)	0.192	2.05	0.765
Glass-Fiber Insulation	0.001703	0	0.963
Polyethylene Vapor Retarder	51.9	2538	0.902
Gypsum Board	0.00336	0	0.901
Asphalt-Impreg. Fiberboard	1.14	50.6	0.923
Asphalt Roofing Paper[1]	51.9	2538	0.902
Extruded Polystyrene Insulation	0.419	12.93	0.524
Polyisocyanurate Insulation	0.0528	2.51	0.773

[1] The regression coefficients of asphalt roofing paper were assumed to be the same as for kraft paper. Since this material has a very low water vapor permeability, little moisture is stored in this material. As a result, it will have very little effect on the predicted moisture content of the plywood roof sheathing. Therefore, the assumed property values may be used in the analysis.

relative humidity difference of approximately 10 percent across each specimen. By using different salt solutions the mean relative humidities across the specimens were varied over the humidity range of 11 percent to 97 percent. Permeability was plotted versus the mean relative humidity across the specimens. Separate measurements conducted at 7°C (45°F) and 24°(75°F) revealed that temperature has a small effect on permeability over this particular temperature range. A detailed description of the permeability measurement method is given in Burch et al. (1992).

Water vapor permeability data were plotted versus the mean relative humidity across the specimen and fit to an equation of the form:

$$\mu = C_1 + C_2 \exp(C_3 \phi) \tag{20}$$

Here the permeability (μ) is expressed in ng/s·m·Pa. The coefficients C_1, C_2, and C_3 were determined by regression analysis and are summarized in Table 5. A plot of the permeance (i.e., permeability divided by thickness) of the materials is given in Figure 7. The asphalt roof shingles and vinyl siding were treated as vapor impermeable. The permeance of the latex paint was assumed to be 689 ng/s·m^2·Pa (12.0 perms).

The mass transfer coefficients for the air boundary layers in contact with the surfaces of the roof

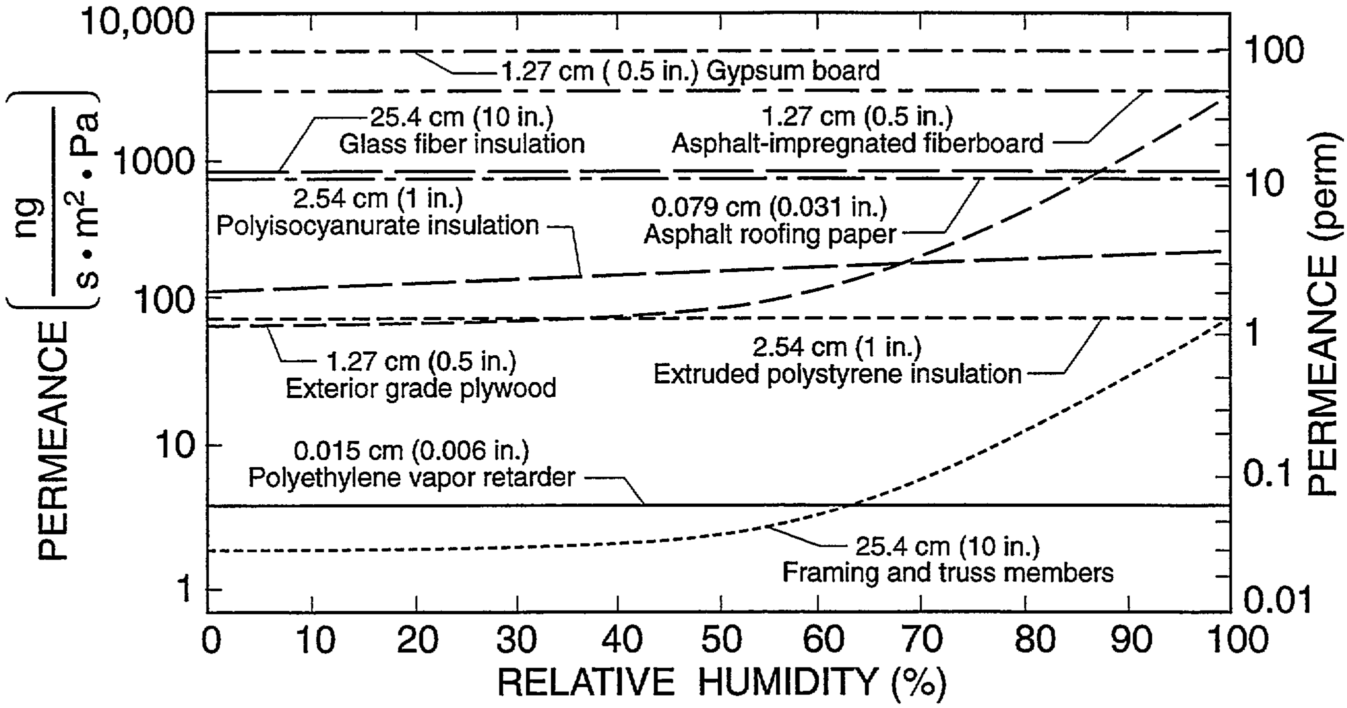


Fig. 7. Water vapor permeances of materials.

Table 5. Permeability Regression Coefficients			
Materials	C_1	C_2	C_3
Exterior-Grade Plywood Sheathing	0.806	0.00163	9.765
Framing and Truss Members	0.442	0.00091	9.86
Glass-Fiber Insulation[1]	182	0	0
Polyethylene Vapor Retarder	0.00053	0	0
Gypsum Board (w/o paint)	63.8	0	0
Asphalt-Impreg. Fiberboard	34.4	0	0
Asphalt Roofing Paper[2]	0.511	0	0
Extruded Polystyrene Insulation	1.75	0	0
Polyisocyanurate Insulation	1.59	1.17	1.041

[1] The permeance of glass-fiber insulation was based on measurements of the permeability of a stagnant air layer. This assumption is reasonable because the glass fibers of the insulation occupy a small fraction of its volume. In this situation, bound-water diffusion along the glass fibers is small compared with molecular diffusion through the predominantly open pore space.

[2] Based on data contained in ASHRAE (1993).

cavity were predicted using the Lewis relationship between heat and mass transfer (Threlkeld 1970).

Liquid Diffusivity

Sometimes liquid water coalesces within the "large" pores of a material. Under this condition, capillary transfer occurs, and liquid diffusivity is the fundamental moisture transport coefficient. The hydraulic conductivity (K) in Equation (1) is related to the liquid diffusivity (D_γ) by the relation:

$$K = -\frac{\rho_d D_\gamma}{\frac{\partial p_l}{\partial \gamma}} \tag{21}$$

where the term in the denominator of the right side of the equation is the derivative of the capillary pressure with respect to moisture content.

In the present study, the materials always operate in the hygroscopic regime, and the above theory did not play a role in these particular calculations.

Air Flows

Roof Cavity Ventilation Rate. Buchan, Lawton, Parent, Ltd (1991) measured sixty attic ventilation rates in twenty houses in several Canadian climates. The houses had different types of attic ventilation with a wide range of ELA's measured using a pressurization technique. For each of the measurements, they also measured the wind speed, wind direction, and temperature difference between the roof cavity and the outdoor environment. We applied Equation 8 to this set of data and used regression analysis to determine the empirical coefficients. The stack coefficient ($C_{\Delta T,c}$) was determined to be a very small value, and in the present analysis it was taken to be zero. The wind coefficient ($C_{v,c}$) was found to be 6.91 x 10^{-5} $(L/s)^2 \cdot (cm)^{-4} \cdot (m/s)^{-2}$ [0.00259 $cfm^2 \cdot in.^{-4} \cdot mph^{-2}$].

A plot of the volumetric attic ventilation rate per unit roof effective leakage area as a function of wind speed is given in Figure 8. Each point represents one of the measurements of Buchan, Lawton, Parent, Ltd (1991). It should be noted that a great deal of scatter exists between the least-squares fit correlation and the measurement points. A contributing factor is that the least-squares fit correlation does not include wind direction and attic ventilation type. Upper and lower bounds for the measured data are also shown on the plot. With the exception of a few points deemed to be outliers, most of the individual measurements fall between the upper and lower bounds.

Since there is no known empirical data for ventilation rates for cathedral ceilings, the NIST CONTAM Model (Walton 1994) was used to predict outdoor to cavity ventilation rates for the cathedral ceiling constructions to be analyzed using MOIST. Because there were either 7.62 cm (3 in.) or 5.08 cm (2 in.) air spaces above the insulation in the ventilated cathedral ceilings, the flow through air spaces of those sizes was modeled. In addition, a thin [0.318 cm (0.125 in.)] high air space was also modeled to predict the air flow in the unventilated cathedral ceilings. It was assumed that the air flow through the 7.62 cm (3 in.) air space was the same as through the open attics.

As one might expect, the CONTAM predictions revealed that the ventilation rate becomes reduced as the height of the cavity air space decreases, and significantly so below 2.54 mm (1.0 in.) due to viscous friction losses. The CONTAM predicted ventilation rates were used to proportion the cavity ventilation rates for the three air space thicknesses, given the open attic value presented above. While this clearly is a rough approximation to the actual cavity flow rates for the cathedral ceilings, it was used in the absence of empirical data. Obviously there is a substantial need for such empirical data to properly pursue modeling of cathedral ceiling performance.

House Natural Ventilation Rate. For the semi-empirical relation (Equation 17), the stack coefficient ($C_{\Delta T,h}$) was taken to be the ASHRAE (1993) value 0.000145 $(L/s)^2 \cdot cm^{-4} \cdot {}^\circ C^{-1}$ [0.0156 $cfm^2 \cdot in^{-4} \cdot {}^\circ F^{-1}$] for a one-story house. The wind speed coefficient ($C_{v,h}$) was taken to be the ASHRAE (1993) value 0.000104 $(L/s)^2 \cdot (cm)^{-4} \cdot (m/s)^{-2}$ [0.0039 $cfm^2 \cdot in.^{-4} \cdot mph^{-2}$] for a one-story house with a Shielding Class of 4.

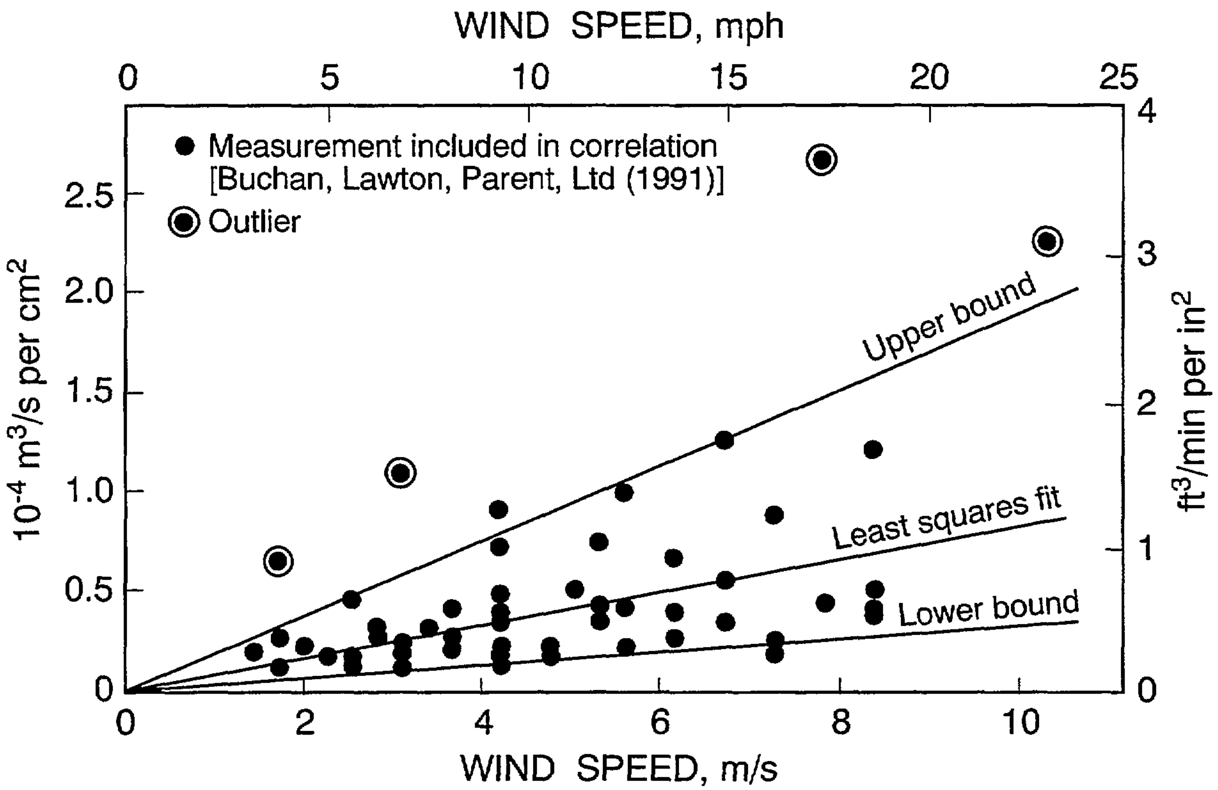


Fig. 8. Volumetric attic ventilation rate per unit roof effective leakage area as a function of wind speed.

Heat

The values of thermal conductivity, density, and specific heat of the materials were taken from ASHRAE (1993).

Other Properties

The long-wave emittance of the materials was taken to be 0.9. The solar absorptances of the asphalt roofing shingles and the vinyl siding applied to the gable end walls were taken to be 0.8 and 0.6, respectively. The roofing shingle solar absorptance of 0.8 was found by Parker, et al. (1993) to be the average value of 34 different colored asphalt shingles. They found values to range from about 0.96 for black shingles to about 0.7 for white ones.

COLD (HEATING) CLIMATE RESULTS (Madison, WI)

We used the new MOIST Attic Model to predict the moisture content of the roof cavity surfaces as a function of time of year. We were interested in determining whether the moisture content of the various roof construction parts was maintained below fiber saturation to prevent degradation of the materials. Thus we focused on the moisture content of a thin 1.6 mm (.063 in.) layer of the surface adjacent to the roof air cavity that was found to have the highest moisture content of any portion of the wood member. In the case of the plywood roof sheathing, which typically was the wettest roof component, this thin layer was at the bottom or cavity side of the plywood. Thus one of the major aims of the analysis was to find out if the moisture content of that plywood lower surface layer ever rose above the fiber saturation point (28 percent moisture content for plywood), which is required for the growth of decay fungi or for delamination to occur.

In addition to examining the moisture content of a surface layer, we also analyzed the relative humidity of the air at the top of the poly vapor retarder above the ceiling gypsum board in those cases where poly existed, and directly above the gypsum board in those cases where there was no vapor retarder. This was done to check for conditions conducive to the growth of mold and mildew. The International Energy Annex has determined that the monthly mean relative humidity at a surface must be above about 80 percent to support mold and mildew growth (IEA 1994), so the simulation results were checked for the existence of that condition.

For each of the 15 roof designs the moisture content and surface relative humidity simulation results are presented together. For each of the three climates the results are presented first for open attic designs and then for the cathedral ceiling designs.

The moisture content and surface relative humidity results presented in this study are weekly average values. Typically the simulations were run for one year, although in a few cases moisture was found to accumulate over the one year period and so additional multi-year simulations were undertaken. In all cases, six months of weather data were used to initialize the reported simulation results to reduce any effect of the assumed initial moisture content and temperature of the construction layers.

We first used the MOIST Attic Model to investigate the moisture performance of the five different roofs on the current practice prototype house in the cold (heating) climate of Madison, Wisconsin.

Cold (Heating) Climate Roof 1: This roof design is the only open attic design in the cold (heating) climate (see Figure 3). It is ventilated with passive roof vents consistent with the 1/300 rule, and there is a poly vapor diffusion retarder just above the gypsum board ceiling. The surface moisture contents of the different roof members at the interior roof cavity surfaces are plotted versus time of year in Figure 9. "N. Plywood" is the north-facing plywood roof sheathing, and "N. Rafter" is the north plywood with a rafter below it. "E. End" is the east end wall asphalt-impregnated fiberboard sheathing. "Int. Wood" is the interior attic trusses, while "Ceiling Insulation and Joist" is both the ceiling insulation and the ceiling insulation over a ceiling joist (their moisture contents are essentially the same). The moisture content of the gypsum board remained less than one percent throughout the year and is not shown.

In all wood members the moisture contents are lowest during summer and rise to a maximum during the winter. The construction part having the highest surface layer moisture content is the north-sloping plywood roof sheathing. The portion of the plywood sheathing in contact with a rafter is fairly similar in moisture content. The south facing plywood is not quite as moist. The peak plywood moisture content is seen to be 19 percent, which is well below fiber saturation (i.e., 28 percent by weight). For all the 14 other roof designs, only the north plywood surface moisture content results are presented, since that roof construction part always has the highest, or close to the highest, moisture content compared to all the other parts.

The surface relative humidity just above the poly also is shown in Figure 9. Note that whereas the plywood moisture content typically peaks in the winter, the surface relative humidity peaks in the summer. That is when warm outdoor air infiltrates into the roof cavity and accumulates on the poly that is relatively cold because the indoor air is air conditioned. Note that conditions conducive to the growth of mold and mildew do not exist for cold (heating) climate roof 1, i.e., the surface relative humidity is below 80 percent.

Cold (Heating) Climate Roofs 2 and 3: These roof designs are ventilated cathedral ceilings (see Figure 3). The plywood surface moisture content and surface relative humidity results are presented, along with those of roof 1 for comparison, in Figure 10. Those two ventilated roofs experience acceptable plywood moisture contents and surface relative humidities. The peak winter moisture content of roof 3 is about the same as for roof 1, while the peak for roof 2 is about one to two percent lower. The fact that roof 2 has about 28 percent more attic ventilation area than roof 1 (because of its greater ceiling area) may be the reason that roof 2 is slightly dryer than roof 1. All three roofs have about the same peak surface relative humidity, which is below the 80 percent level required for the onset of mold and mildew.

Cold (Heating) Climate Roofs 4 and 5: These roof designs are unventilated cathedral ceilings (see Figure 3). The performance of roofs 4 and 5 is compared to that of roof 2 in Figure 11. The moisture contents rise during the winter but they remain considerably below fiber saturation. The ceiling-insulation interface RH's are seen to rise during the summer, but they never rise about the critical 80 percent level.

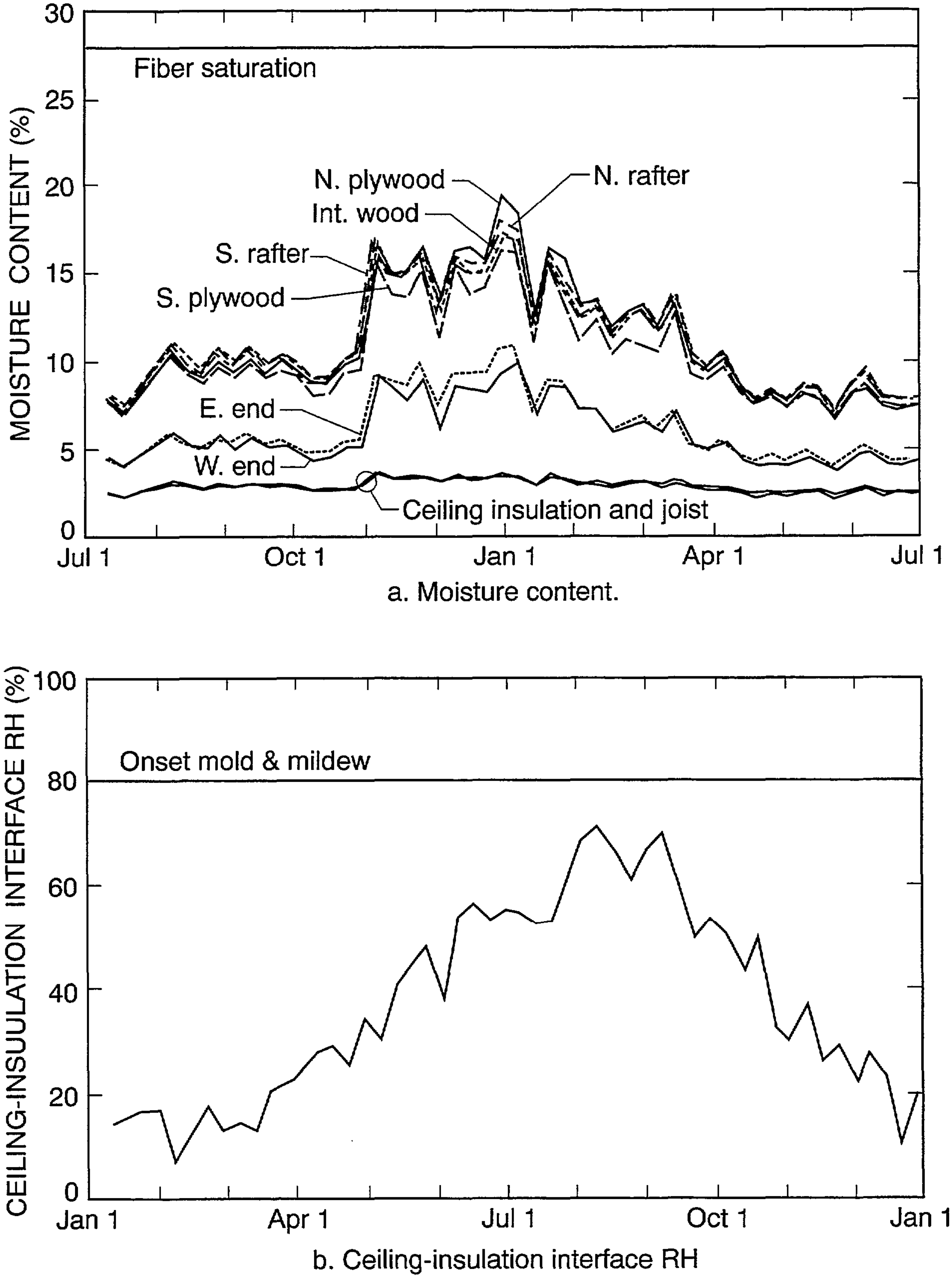
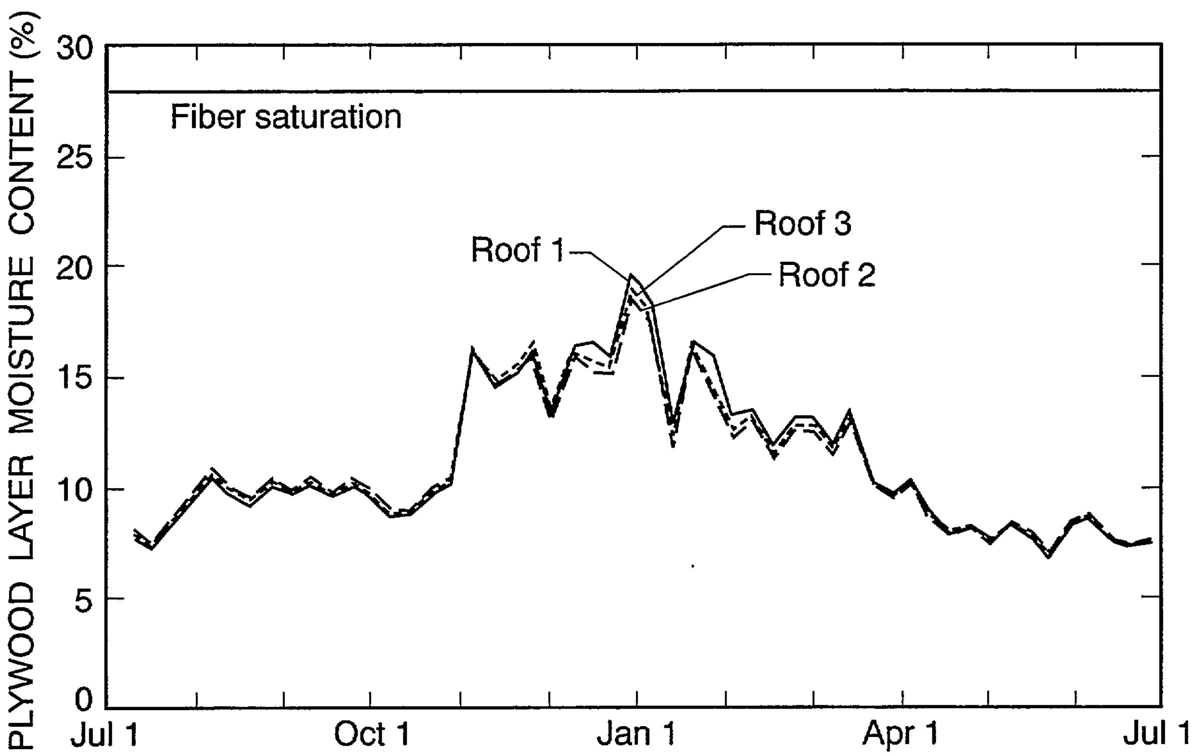
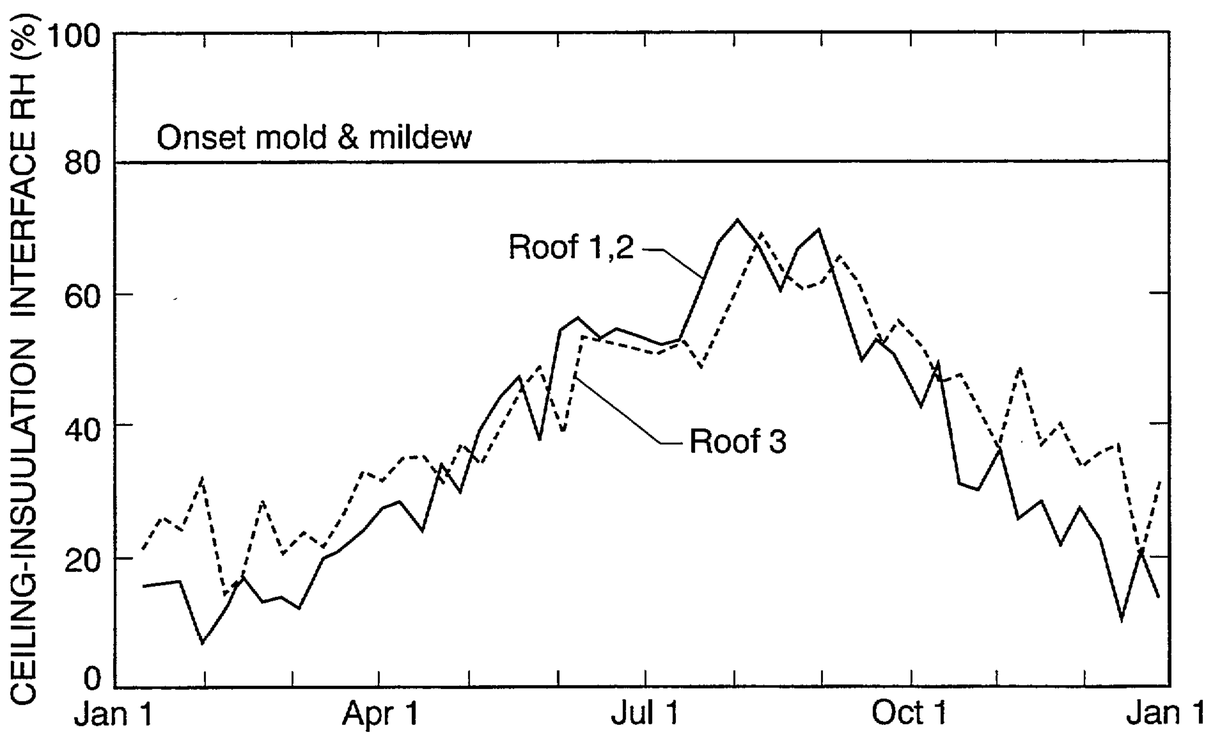


Fig. 9. Moisture performance of cold (heating) climate roof 1 located in Madison, WI.



a. Plywood layer moisture content



b. Ceiling-insulation interface RH

Fig.10. Moisture performance of cold (heating) climate roofs 1, 2, and 3 located in Madison, WI.

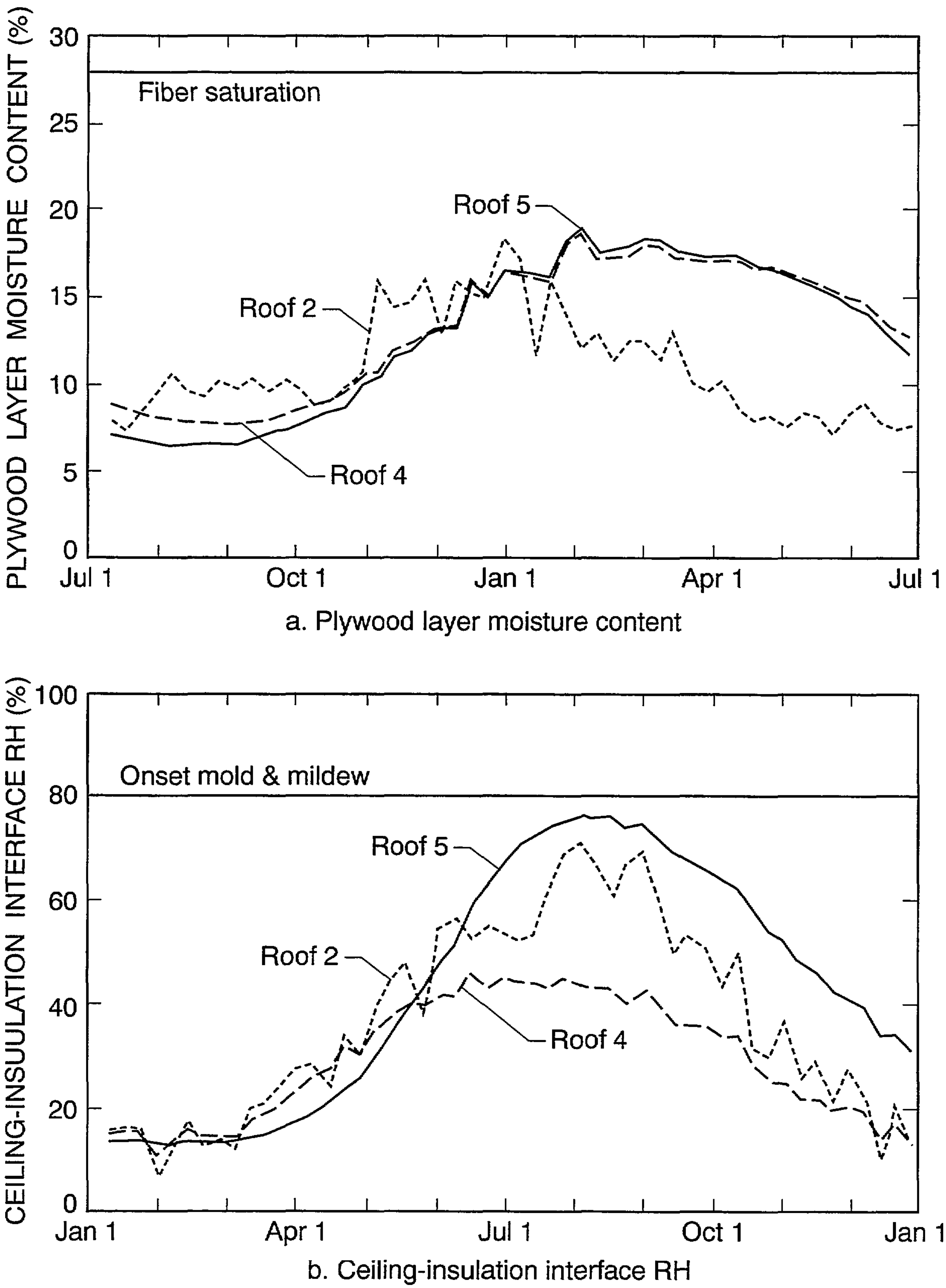


Fig. 11. Moisture performance of cold (heating) climate roofs 2, 4, and 5 located in Madison, WI.

Note that in roof 4, which has two layers of plywood roof sheathing (see Figure 3), the moisture content shown in Figure 11 is that of the upper sheathing.

It can be seen that roofs 4 and 5 perform similar to each other from a moisture point of view. Their peak moisture contents are very similar to those of roofs 1, 2, and 3. More importantly, however, the results suggest that moisture is accumulating in both of the unventilated roofs (4 and 5), since the moisture content at the end of the simulation year (July 1) is greater than that at the start of the simulation (the previous July 1). If there were no accumulation, these two moisture contents would be the same. Note that it was assumed in these unventilated cases that the ceiling ELA was 194 cm^2 (30 $in.^2$), whereas the roof ELA was assumed to be only 6.5 cm^2 (1 $in.^2$). Thus with the assumed conditions for these unventilated designs, the opportunity for accumulation exists.

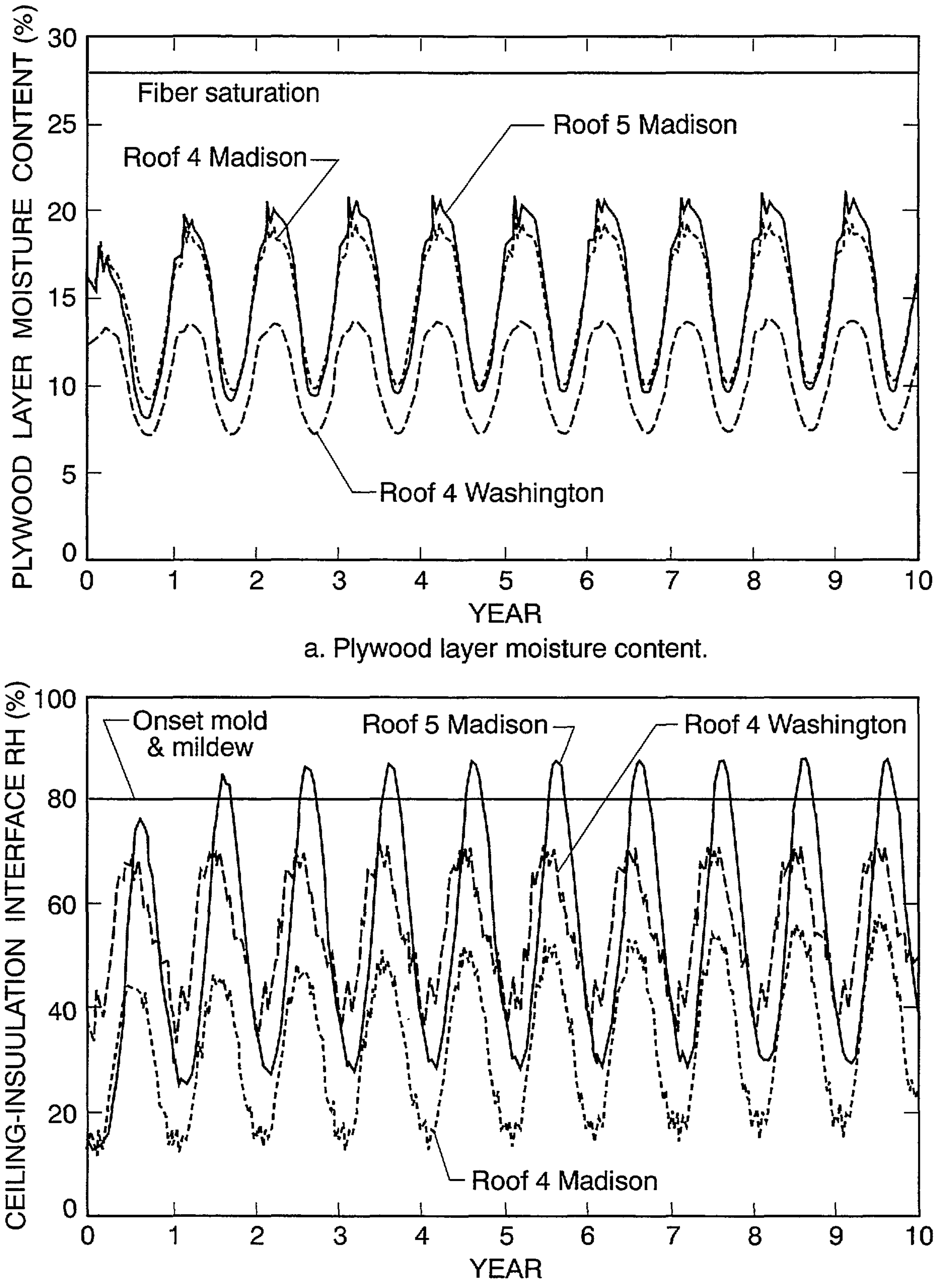
To check this, the simulations were repeated for a ten year period. Those results are shown in Figure 12. The roofs do eventually reach a state of long term moisture equilibrium in a few years. It appears that roof 4 reaches steady-periodic annual conditions before roof 5.

While the plywood sheathing moisture content does not reach fiber saturation, the interface relative humidity does get above the point of mold and mildew onset for about a month in the summer for roof 5. Note that it has a vapor barrier that keeps the roof from readily drying to the indoor air in the summer. Roof 4 can dry out to the indoor air more readily because of the absence of a vapor retarder just above the ceiling gypsum board. Removal of the vapor retarder in roof 5 should lower the interface relative humidity. That needs to be checked in the follow up parametric sensitivity study.

MIXED CLIMATE RESULTS (Washington, D.C.)

The model was next used to investigate the moisture performance of the four mixed climate roof constructions with the assumed current practice prototype house. Two of the roofs were open attic types, whereas the other two were cathedral ceiling types (see Figure 4).

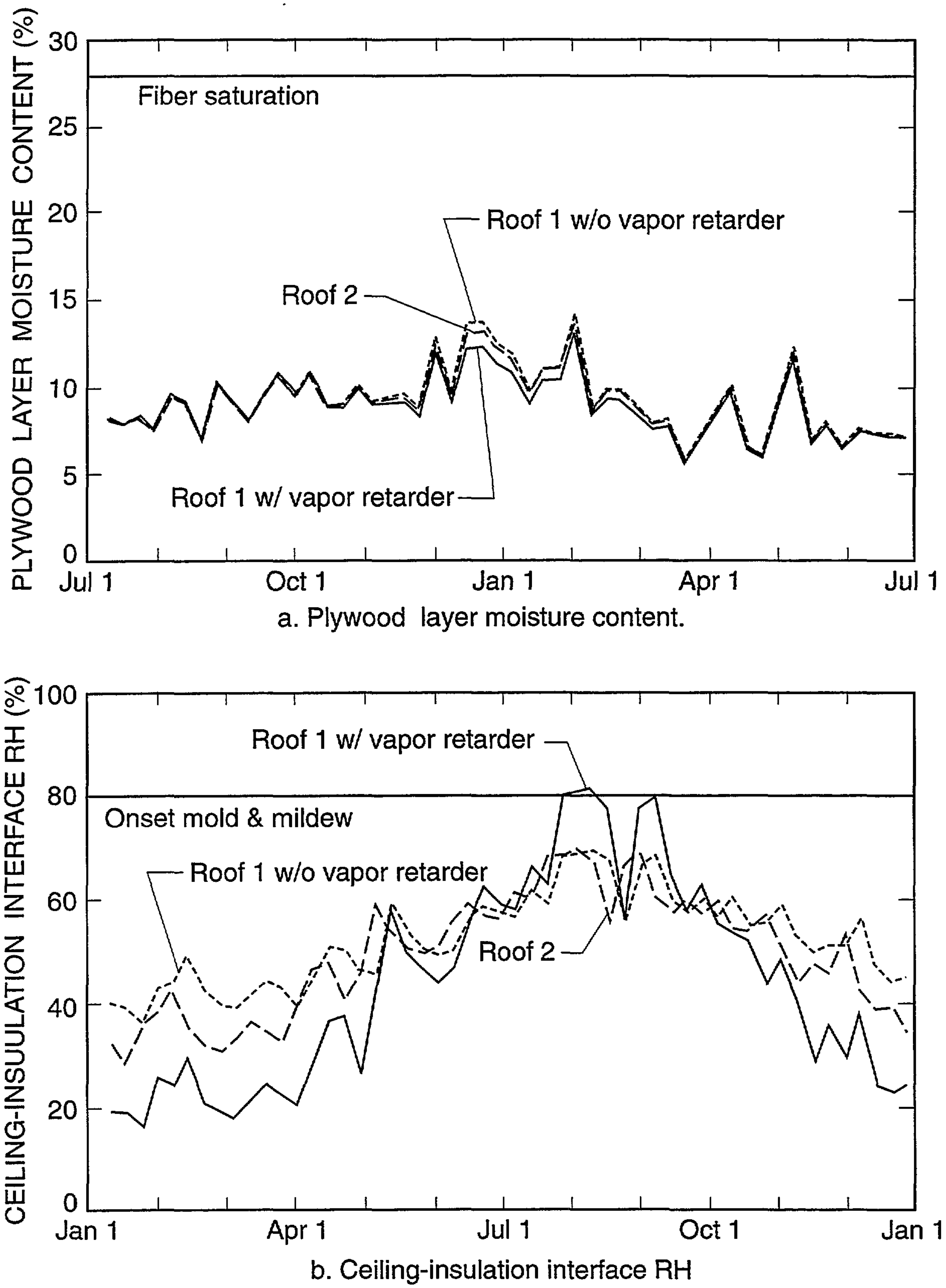
Mixed Climate Roofs 1 and 2: These roof designs are the ventilated open attic type (see Figure 4). Like cold (heating) climate roof 1, they are ventilated with passive roof vents consistent with the 1/300 rule. There is a poly vapor diffusion retarder just above the gypsum board flat ceiling for roof 1, whereas roof 2 does not have a vapor retarder but uses a well sealed airtight drywall approach (we assumed a ceiling ELA for this one case of 48.4 cm^2 (7.5 $in.^2$). Roof 1 had a ceiling ELA of 194 cm^2 (30 $in.^2$). For each roof the moisture contents of the lower plywood surface layer are plotted versus time of year in Figure 13. All of these roofs have a lower moisture content than any of the cold climate roofs. Importantly, neither of these ventilated roofs was close to fiber saturation. Somewhat surprisingly, and counter-intuitively, roof 2 with its lower ceiling ELA actually had a slightly higher winter peak plywood moisture content. The difference between these results will be explored in more detail, along with other parametric sensitivity analyses of the 15 roof constructions, in a follow up report. Roof 1 with a vapor retarder gets just above the critical 80 percent RH level for a few weeks in the summer. However, the duration of this condition may be insufficient to give rise to mold and mildew growth.



a. Plywood layer moisture content.

b. Ceiling-insulation interface RH

Fig. 12. Ten year simulations for cold (heating) climate roofs 4 and 5 in Madison, WI and mixed climate roof 4 in Washington, DC.



a. Plywood layer moisture content.

b. Ceiling-insulation interface RH

Fig. 13. Moisture performance of mixed climate roof 1(with and without a vapor retarder) and roof 2 in Washington, DC.

Roof 2 with its more permeable ceiling (without a vapor retarder) has a lower interface relative humidity (RH) that is well below the onset level for mold and mildew. That is one good reason for leaving out the vapor retarder in roof 2. Thus it was decided to examine whether removing the vapor retarder in roof 1 would help its summer performance. The results are shown in the bottom plot of Figure 13. The interface RH is then about the same as that of roof 2 without a vapor retarder. Thus without any further parametric analysis it appears that eliminating the ceiling vapor retarder in open attics in a mixed climate may actually be a good idea. That allows the moisture at the bottom of the insulation to more readily diffuse into the living space during the summer where it is removed by the air conditioning system.

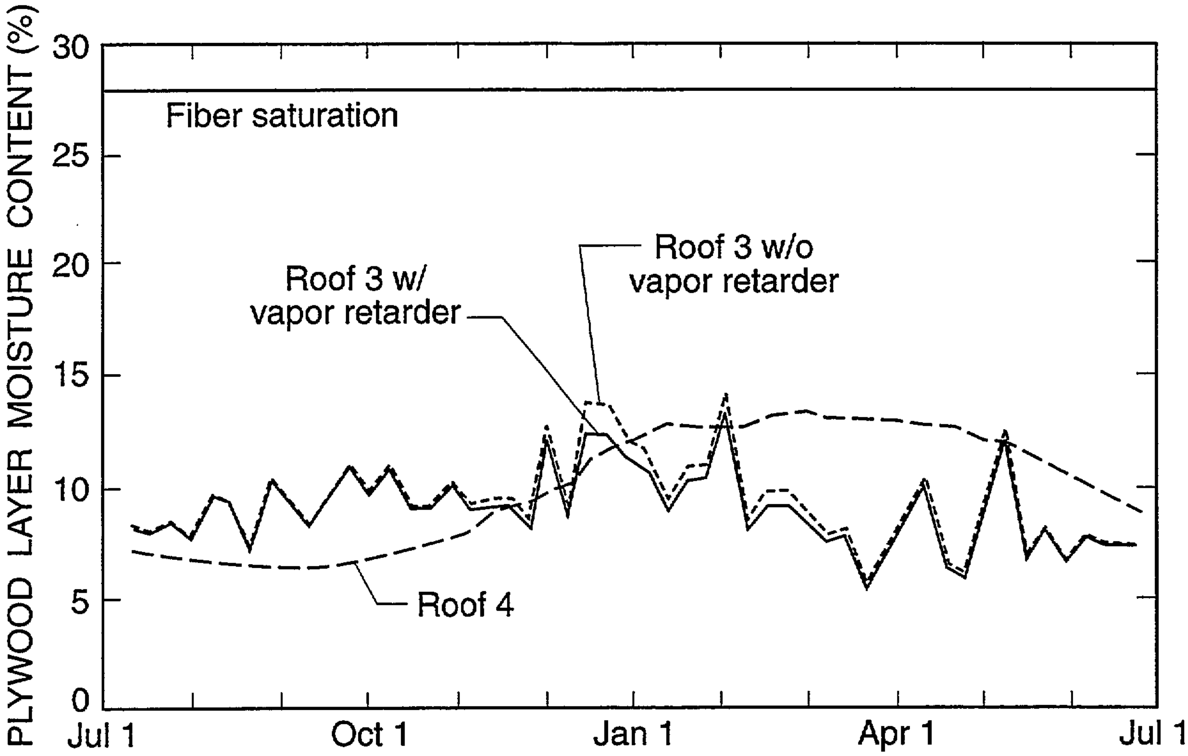
Not shown are results for roofs 1 and 2 without ventilation. Removing the ventilation of roof 1 also reduces the interface RH about the same amount as removing the vapor retarder, but the winter peak plywood moisture content is more adversely affected (reaching a peak of about 21 percent). In roof 2 without ventilation the interface RH is the lowest of the cases investigated, but the peak plywood moisture content is even higher and approaches fiber saturation. Hence eliminating ventilation in either case does not appear to be wise. These results indicate that leaving out the vapor diffusion retarder is the better approach in mixed climates.

Mixed Climate Roofs 3 and 4: These roof designs are cathedral ceiling types---roof 3 has ventilation above the batt insulation and roof 4 has no ventilation space, although there is rigid insulation above the plywood sheathing (see Figure 4). Both roofs employ a poly vapor retarder. The simulation results are shown in Figure 14. The two roofs perform well in terms of the plywood surface moisture content. However, while the unventilated roof 4 performs well from a mold and mildew point of view, the ventilated cathedral type roof 3 with a vapor retarder experiences brief summer periods when the interface RH is above 80 percent, and hence the potential for the growth of mold and mildew exists. However, the duration of these periods may be insufficient (i.e., less that one month) to give rise to mold and mildew growth. The beneficial effect of removing the vapor retarder in roof 3 and allowing moisture at the interface to diffuse into the indoor space rather than collect is also shown in Figure 14. There is no serious adverse impact of removing the vapor retarder on the plywood moisture content in this mild winter climate, although further parametric sensitivity analysis should be performed to further investigate this result.

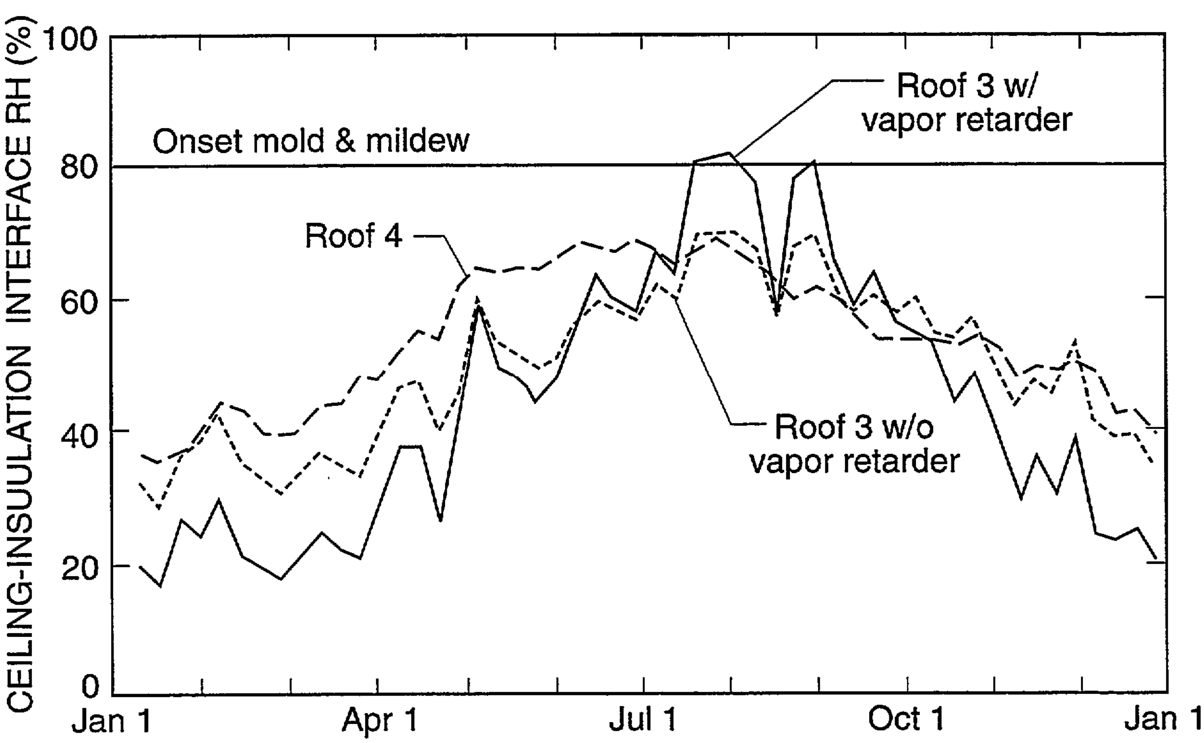
COOLING (HOT AND HUMID) CLIMATE RESULTS (Lake Charles, LA)

We next used the model to investigate the moisture performance of the six hot and humid climate roofs with the current practice prototype house. All of the six roofs were the open attic type (see Figure 5). The first four employed a ceiling vapor retarder just above the gypsum board, whereas the last two did not employ a vapor retarder. Roof 6 differed from roof 5 only in that it used a combination of rigid and fiberglass batt insulation, whereas roof 5 used only fiberglass insulation (similarly to the first four roofs). From a moisture performance point of view the first four roofs are the same, so in reality there were only three roof types to analyze.

Cooling (Hot and Humid) Climate Roofs 1-4, 5, and 6: The simulation results for roofs 1-4, along with those for roofs 5 and 6 are shown in Figure 15.

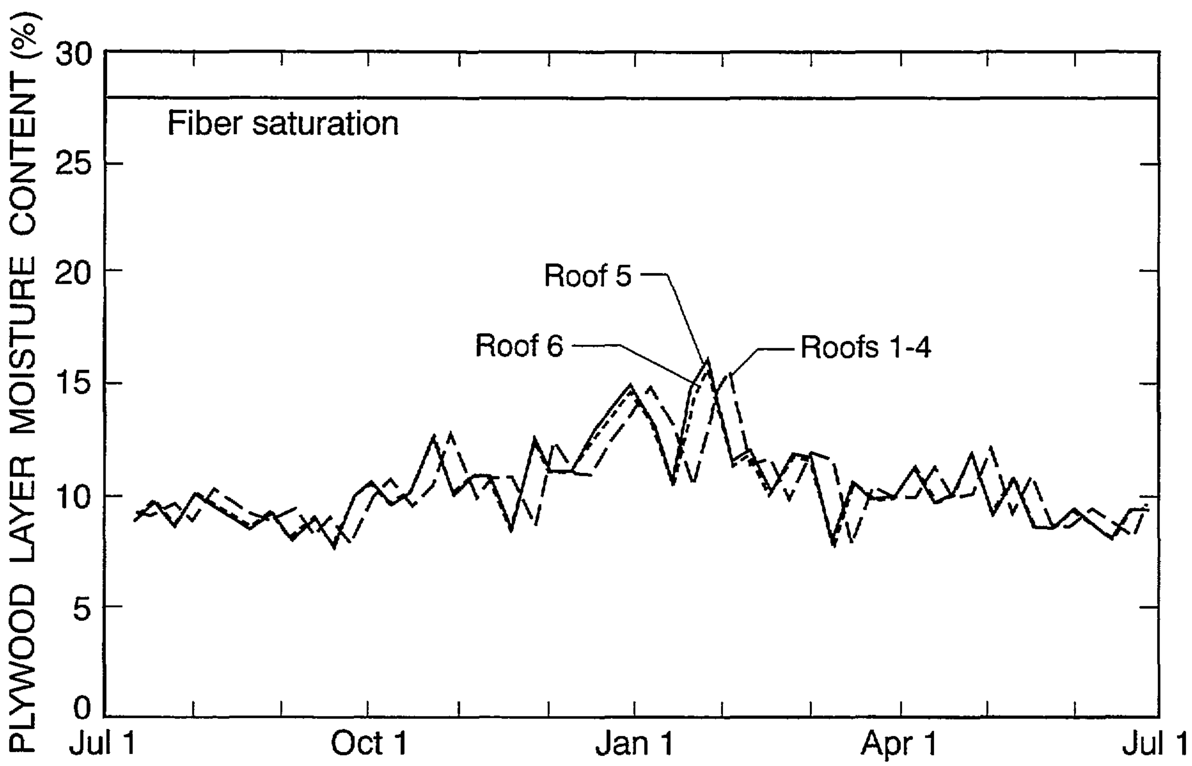


a. Plywood layer moisture content

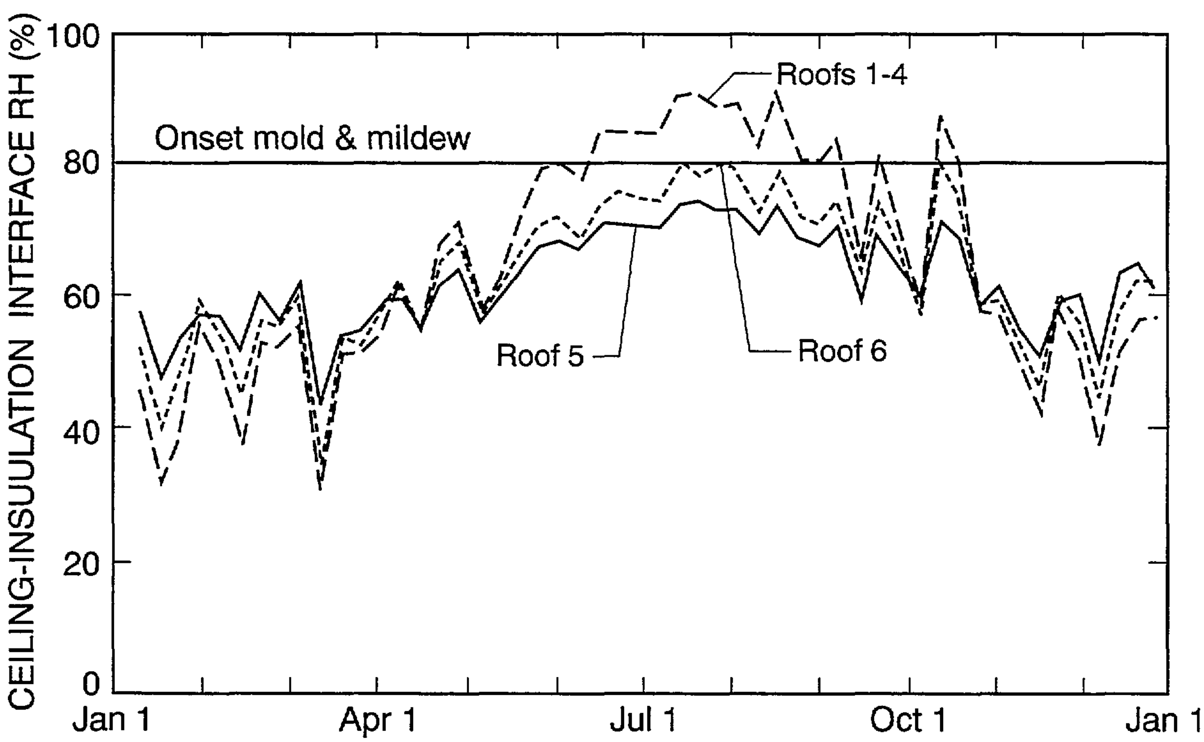


b. Ceiling-insulation interface RH

Fig. 14. Moisture performance of mixed climate roof 3 (with and without a vapor retarder) and roof 4 in Washington, DC.



a. Plywood layer moisture content.



b. Ceiling-insulation interface RH

Fig. 15. Moisture performance of cooling (hot and humid) climate roofs 1-4, 5 and 6 located in Lake Charles, LA.

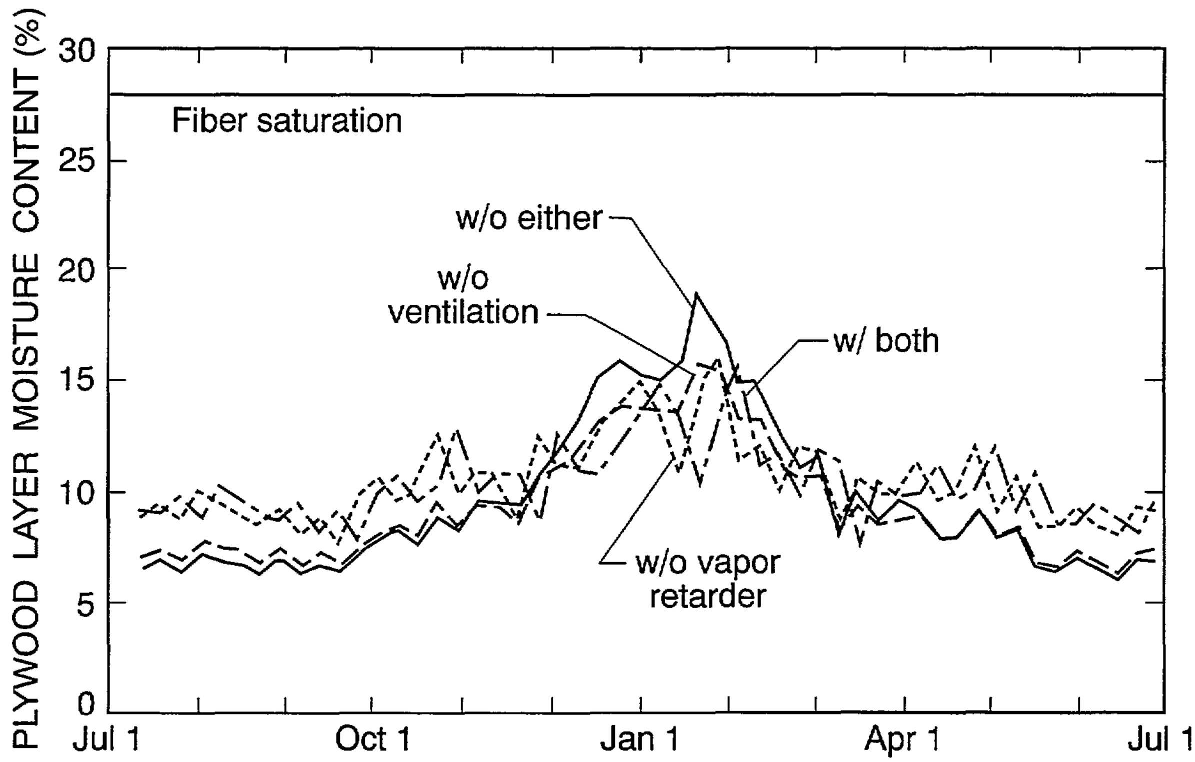
The results clearly show that the plywood stays quite dry for all the roof designs. While the cooling (hot and humid) climate is quite conducive to the growth of decay fungi from the point of view of temperatures being quite warm, these results point out that it is very difficult to get wood wet enough to decay. What is surprising is the fact that the plywood sheathing in all of the cooling (hot and humid) climate roofs has a higher moisture content than any of the mixed climate roofs. Fortunately, in no case is that a problem. Since the Lake Charles winter climate is much less severe than that of Washington, D.C., a possible explanation is that the winter indoor relative humidities are sufficiently higher in Lake Charles to cause that result.

Furthermore, for the two roofs without a ceiling vapor retarder (5 and 6) the interface RH did not rise above the critical 80 percent level, although it was close for roof 6 because the 25.4 mm (1.0 in.) of rigid insulation adjacent to the gypsum board acted somewhat like a vapor retarder that minimized summer diffusion of moisture into the indoors. Thus roof design 5 had better moisture performance than roof 6. However, for roofs 1-4 the presence of a ceiling vapor retarder caused the interface RH to rise well above the 80 percent level for about three months in the summertime. That is the worst of any of the roofs analyzed in any climate and clearly is unacceptable moisture performance. The impact of removing the vapor retarder and also eliminating the attic ventilation in roofs 1-4 is shown in Figure 16. Removing the vapor retarder is helpful as is closing or removing the attic vents, but removing the vapor retarder is the most helpful. That is because even without attic ventilation the vapor retarder and its influence still exists. Closing the vents reduces the influx of warm moist outdoor air into the roof cavity where its water vapor can condense on the vapor retarder surface that is cooled by indoor air conditioning. Doing both provides the best conditions from a mold and mildew point of view, while not adversely impacting the plywood moisture content very much at all.

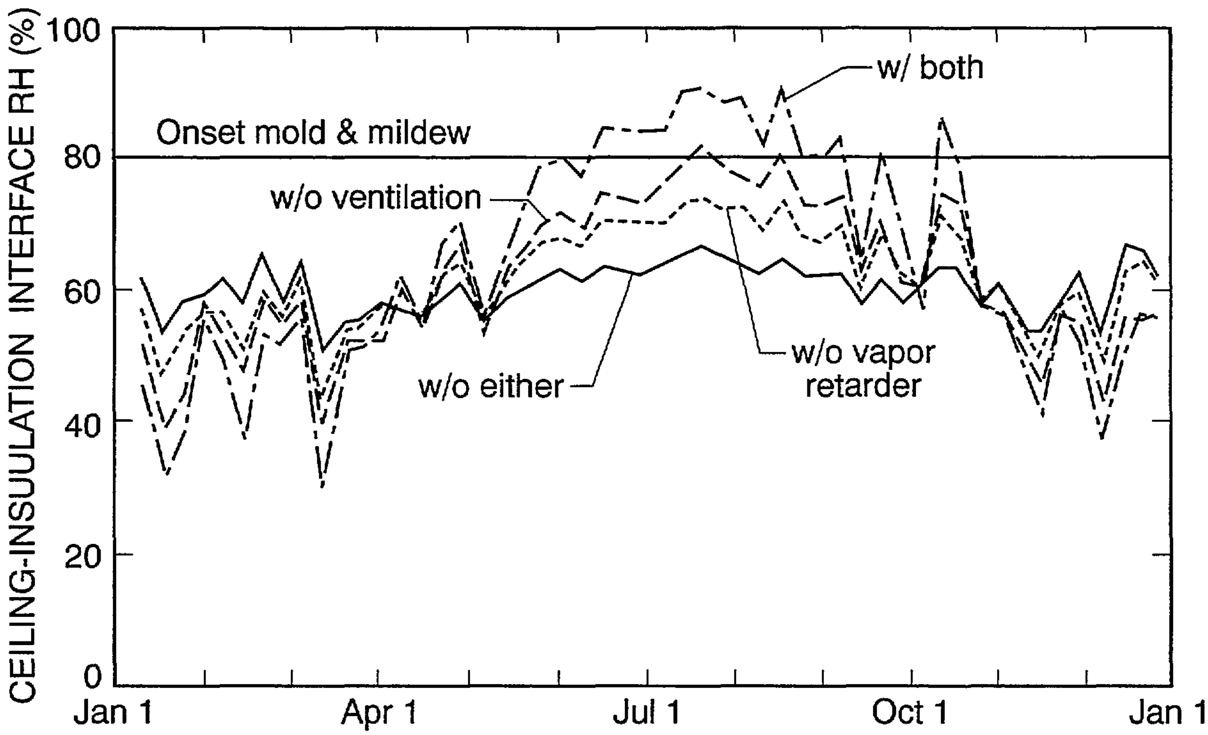
SUMMARY AND CONCLUSIONS

A new mathematical model, called the MOIST Attic Model, that predicts the transfer of moisture and heat in roof cavities, has been presented. It allows assessment of the moisture performance of open attics as well as cathedral ceilings. This model performs a transient heat and moisture balance on a roof cavity at hourly time steps, and includes the storage of moisture and heat at the building envelope parts comprising the roof cavity. The air flow from the house through ceiling air leakage sites into the roof cavity is predicted as a function of time using a stack effect model and the ceiling ELA as an input. The ventilation rate of the roof cavity with outdoor air is predicted as a function of wind speed using a semi-empirical model with the roof ELA serving as an input. The relative humidity in the house below is permitted to vary during the winter and is predicted from a moisture balance of the whole building with the house ELA and indoor moisture production rate serving as inputs.

The above model was subsequently used to predict the moisture performance of a current practice site-built prototype house with 15 different roof designs constructed in compliance with the *U.S. DOE Moisture Control Handbook*. Those 15 roof constructions were suggested in 1991 as the best designs to control moisture in roofs, but at that time there was no readily available computer model to check their moisture performance. So, in addition to developing the new moisture model, one of the goals of the project reported herein was to apply the new model to the 15 roofs to assess their



a. Plywood layer moisture content.



b. Ceiling-insulation interface RH

Fig. 16. Moisture performance of cooling (hot and humid) climate roofs 1-4 with a vapor retarder and ventilation, without a vapor retarder, without ventilation, and without both, located in Lake Charles, LA.

moisture performance.

Of the 15 roof constructions, nine were the conventional open attic type (six were distinct from a moisture point of view) and six of the designs were cathedral ceilings (three ventilated and three unventilated). Some of the roofs had an interior vapor retarder installed in their ceiling construction, and some did not. Passive roof ventilation, where incorporated, was installed consistent with the 1/300 rule. Moisture performance was analyzed in three distinct climates: cold or heating (Madison, Wisconsin), mixed (Washington, D.C.), and cooling or hot and humid (Lake Charles, Louisiana). The roof construction material with the highest moisture content was found generally to be the lower surface layer of the north-facing plywood roof sheathing. Its moisture content was predicted as a function of time of year, as was the relative humidity at the bottom of the insulation adjacent to the poly vapor retarder above the gypsum board ceiling, or just above the gypsum board if no poly was present. The International Energy Agency Annex 14 *Guidelines and Practices* (IEA 1990) indicates that a monthly mean surface relative humidity exceeding 80 percent is conducive to mold and mildew growth.

For the cold or heating climate (northern United States), all the five roofs in the *Moisture Control Handbook* were observed to perform satisfactorily from a moisture content point of view. That is, for all the roof constructions the peak moisture content of the wettest wood in each roof was always observed to be considerably below fiber saturation, thereby indicating little or no risk of material degradation such as wood decay or delamination. Moreover, the peak moisture contents for all the cold climate roof constructions were about the same, whether the roof was an open attic or a cathedral ceiling (ventilated or unventilated). The satisfactory performance was achieved in most of the roof constructions by vent openings installed in the roof cavity consistent with the 1/300 rule. The unventilated cathedral ceilings surprisingly accumulated moisture for a few years before their peak moisture content stabilized from year to year. However, in none of the roofs did the moisture content ever get above about 21 percent, which is well below the fiber saturation level of 28 percent for plywood.

In the cold climate, all of the roofs except one unventilated roof, also performed well from a mold and mildew point of view. That is, none of the roof constructions, except roof 5, had a surface relative humidity at the top of the poly vapor retarder that was above the 80 percent critical level for more than a month, which is required for the growth of mold and mildew. For the mixed climate (central United States), all the four roofs performed satisfactorily in terms of the peak plywood moisture content. The plywood in the roofs of this less severe winter climate was drier than in the cold climate roofs. Surprisingly, the mixed climate roofs were also slightly drier than the cooling (hot and humid) climate roofs in that much less severe winter climate, likely due to lower indoor relative humidities in the mixed climate.

The two mixed climate roofs without a vapor retarder just above the ceiling gypsum board (one a ventilated open attic and the other an unventilated cathedral ceiling) had relative humidities at the top surface of the ceiling that were below the 80 percent critical level conducive to the growth of mold and mildew. However, the two roofs with a vapor retarder just above the ceiling (one a ventilated open attic and the other a ventilated cathedral ceiling) had relative humidity values at the top of the poly just above the 80 percent level for about three weeks in the summer. Yet removal of the vapor retarder in both cases reduced the interface RH to well below the 80 percent level without hardly any adverse impact on the plywood moisture contents. *This analytical study indicates that the vapor retarder should be removed from the mixed climate designs. However, this finding must await the results of a follow up sensitivity analysis that is underway.*

For the cooling or hot and humid climate (southeastern United States), the plywood sheathing peak moisture content in all of the six roof constructions (ventilated open attic type) always was well below the critical fiber saturation level necessary for the growth of wood decay. However, cooling (hot and humid) climate roofs 1-4 (which are identical from a moisture point of view) were found to be at risk for mold and mildew growth at the upper surface of the 6 mil polyethylene vapor retarder located between the gypsum board ceiling and the glass-fiber insulation. At that location, the surface relative humidity was predicted to rise above 80 percent during a 3-month summer period. Moisture from the hot and humid outdoor air (Lake Charles, LA) was transported to the upper surface of the glass-fiber insulation by attic ventilation. This moisture was subsequently transferred by diffusion downward to the upper surface of the polyethylene. The polyethylene served as a dam and caused moisture to accumulate at its upper surface, which was cooled by the air conditioned indoor air below.

Roof 5 of the cooling (hot and humid) climate did not contain a polyethylene vapor retarder and was found to perform satisfactorily. Roof 6 with fairly impermeable rigid insulation just above the gypsum board had a summer peak interface relative humidity that was right at the 80 percent critical level. For roofs 1-4 and 6, once either the vapor retarder was removed or the attic ventilation was sealed off or eliminated, or both, then the surface relative humidity dropped sufficiently to avoid the possible growth of mold and mildew. Without those changes to eliminate the use of a vapor retarder or attic ventilation, four of the six cooling (hot and humid) climate roof designs would have to be considered unsatisfactory. The roof design with no vapor retarder performed satisfactorily. Incidently, removing the vapor retarders in the cooling (hot and humid) climate roofs was found to provide lower surface relative humidities than eliminating the attic ventilation. The best moisture performance was with both the ventilation and the vapor retarder removed.

It is worth noting that Lstiburek and Carmody changed some of the roof constructions recommended in 1991 in the *U.S. DOE Moisture Control Handbook* (Lstiburek and Carmody 1991) in their later revised hard copy version of the Handbook (Lstiburek and Carmody 1993). For example, they were aware that the vapor retarder in the cooling (hot and humid) climates might cause a problem with mold and mildew, so they removed it from the roof designs in that climate. As shown in this study, that makes them perform well, in that they are not likely to lead to the growth of mold and mildew.

Overall, in all 15 roof constructions, independent of climate, the peak moisture contents were well below the fiber saturation level. In any roof, the highest moisture content was 21 percent for the plywood roof sheathing, which is much lower than its 28 percent fiber saturation level. Yet moisture-induced material degradation occurs only when the moisture content of a material approaches or exceeds fiber saturation. Therefore, based on the simulations run to date, moisture-induced material degradation should not be a problem in these constructions. However, that conclusion will be re-evaluated after further parametric sensitivity analyses now underway as a follow up study are completed.

Variations in the outdoor climate were found to have much less effect on the sheathing moisture content than reported in a previous roof study (Burch 1995). In the present study, the indoor relative humidity was permitted to vary during the winter and was calculated from a moisture balance of the whole building. In the previous study, the indoor relative humidity was maintained at a constant level during the simulation. The effect of climate is diminished in the present study because lower indoor relative humidity occurs during the winter in colder climates, which acts to decrease moisture transport into the roof cavity.

The results of this investigation also point out that when assessing the moisture performance of roof constructions, one must analyze not just the maximum moisture content of the various wood members to determine if the construction could degrade. It is also necessary to assess the surface relative humidity at critical locations to see if it is high enough in the summertime to cause the growth of mold and mildew that could be a health risk. While all of the roof constructions performed well from a moisture and material degradation point of view, some did not from a mold and mildew and health point of view.

The current roof moisture control practices required in most states by building codes (i.e, installing an interior vapor retarder in the ceiling construction and installing roof cavity vents consistent with the 1/300 rule) were found to be effective in cold climates. That is, the peak moisture content of the roof sheathing was maintained well below fiber saturation in tight houses having fairly high indoor relative humidity. However, these same moisture control practices did not perform acceptably in mixed or hot and humid climates. Here moisture from the outdoor environment accumulated at the upper surface of the vapor retarder where the surface relative humidity approached a saturated state during the summer. This location provided a conducive environment for mold and mildew growth. This analytical study indicates *that a ceiling vapor retarder not be required or used in a mixed or cooling (hot and humid) climate. Furthermore, roof cavity ventilation should not be required in cooling (hot and humid) climates.*

RECOMMENDATIONS FOR FURTHER STUDY

Need for Parametric Sensitivity Analysis

This report describes the moisture performance of the 15 roof constructions in the *U.S. DOE Moisture Control Handbook* based on a limited set of assumed conditions and inputs to the computer model. Yet based on previous experience with wall modeling (Tsongas et al. 1995), it is clear that many factors can affect the performance of walls, and likely roofs as well. Thus it would be especially useful to examine the effect of a number of parameters that might influence the overall moisture performance of the different roof constructions. It would be worth analyzing their effects on roof moisture content, interface relative humidity, the indoor RH, the ceiling air exfiltration rate, and the roof cavity or attic air temperature. The sensitivity of the moisture performance results to the various factors would be explored by varying each of the factors over an appropriate range.

Factors or parameters whose effect on roof moisture performance is worth exploring include:

- ceiling ELA
- roof ELA
- total house ELA (house tightness)
- amount of roof passive ventilation (is 1/300 optimum?)
- amount of roof mechanical ventilation
- shingle solar absorptance
- presence of a ceiling vapor retarder
- amount of indoor mechanical ventilation or dehumidification
- house humidification (fixed indoor RH during non-summer months)
- indoor moisture generation rate
- indoor temperature setting
- other weather sites in the three climate zones

In fact such parametric analysis of roofs of manufactured homes has recently been completed (Burch, Tsongas, and Walton 1996). Such a sensitivity analysis for site-built homes is also underway as the next detailed follow-up to this initial report on roof moisture modeling of the performance of the proposed 15 roof constructions. Only after the completion of that analysis can the moisture performance of the 15 designs be fully evaluated.

Roof Moisture Performance in Different U.S. Climates

The results of this report clearly show that similar roofs do not perform alike in different climates of the U.S. For example, utilizing attic ventilation and a ceiling vapor retarder is a good idea in northern cold climates, and yet it is not at all wise in cooling (hot and humid) climates. Thus building codes should not uniformly require attic ventilation and/or a ceiling vapor retarder in all climates of the U.S. Unfortunately, other than for the three climates examined, it is not at all clear in which specific climates vapor retarders are useful as a moisture control strategy.

In order to clearly decide which distinct climatic regions should have which requirements and which should not, it would be worthwhile repeating the type of modeling undertaken in this report for a number of different climates across the nation, as noted in the list above. For example, no modeling has been done for relatively mild cold climates such as Portland, Oregon or New York City, or for hot and dry mixed climates such as those of the southwest (Arizona or southern California), or for other mixed climates such as those in Texas, Arkansas, or Tennessee. In addition, concurrent with examining moisture conditions, it would be worthwhile to look at energy use considerations (heat loss or gain through ceilings) in making decisions. The new roof moisture model can be used to examine ceiling heat flux values for different roof conditions or constructions.

Uncertainties Regarding Attic Ventilation

The attic simulation program described and applied herein appears to be a valuable new tool for investigating potential attic moisture problems in both site-built and manufactured housing. One weakness in the model is the lack of empirical information regarding leakage areas and especially the amount of air flow through attic cavities. The air exchange rate between the attic cavity and the outdoors was modeled using the LBL natural infiltration model (see Equation (8)) (Sherman and Grimsrud 1980) with stack and wind coefficients obtained from measurements on 60 site-built houses. Typical manufactured housing is generally characterized by shallower roof pitches and lower attic volumes, as well as fairly airtight ceilings, and so the attic ventilation characteristics may be quite different than in site-built homes. Unfortunately, there is no known empirical data available for attic air exchange rates in manufactured homes. Moreover, there really is insufficient data for site-built homes as well. Such information is clearly needed for both types of homes.

In addition, better information is needed on the amount of unintentional roof leakage area in site-built and manufactured homes. There also is uncertainty about the typical ELA values of ceilings in site-built and manufactured homes. Moreover, the impact of the stack effect in cooling (hot and humid) climates also warrants further inspection. It was neglected in this study based on cold climate Canadian data (Buchan, Lawton, Parent Ltd 1991). Yet attic modeling by Parker, Fairey, and Gu (1991) showed that buoyancy effects in attics in hot and humid climates may be important. Their analysis indicated that buoyancy was important in properly describing energy flows, but they did not focus on moisture transfer. That merits further investigation.

It would be most worthwhile to fit some site-built and manufactured homes with different commonly-used attic ventilation systems and measure the air exchange rates with tracer gases over both short and long term periods. The field data could then be broken down to determine typical stack and wind coefficients for the LBL infiltration model for each type of ventilation. It also would be important to try to determine the impact of wind direction in such a study. Further, it would be most important to monitor the attics under conditions with high moisture generation rates inside the homes that would most likely lead to adverse conditions in the attics or roof sheathing. Field testing should be undertaken in each of the three distinct climates investigated in this study since roof performance is so climate dependent. Clearly such information is needed to validate the model.

Finally, there are still some prominent building scientists who believe that roofs should not be ventilated. To unequivocally decide whether it is better to ventilate or not, it would be extremely worthwhile to test two site-built and two manufactured houses side by side. One of each type would have attic ventilation and the other would not. A comparison of their moisture conditions would hopefully settle this issue once and for all.

Shingle and Sheathing Temperatures

For a number of reasons, building scientists and others associated with the building industry would like to know the effect of roof ventilation on the temperature of roof sheathing and roof coverings such as asphalt shingles. That is true for roofs with both open attics above flat ceilings and cathedral ceilings. The impact on those temperatures of other factors such as the color of the exterior surface of the roof covering as well as the type of roof covering (e.g., asphalt shingles, shakes, tile, metal, etc.) is also of interest. The new MOIST Attic Model is well suited to help assess the impact of ventilation and other factors on roof covering and sheathing temperatures. Thus, it is recommended that such modeling with the new roof model described herein be undertaken.

Model Validation

The MOIST Attic Model appears to be giving reasonable results. Most importantly, its predictions are in general agreement with what few field measurements have been made. For example, predictions for open attic roof sheathing in Madison, Wisconsin are well within a few percent of field measurements made in homes in Montana, which has a similar winter climate. The average value measured during mid-winter was 15.8 percent (Tsongas 1990). Harrje et al. (1986) measured similar mid-winter plywood sheathing moisture contents in town houses in New Jersey. Furthermore, some of the predicted trends noted in this report appear to be consistent with trends measured at the Small Homes Council Roofing Research Facility in Illinois. This is all compelling evidence that the model is making reasonable predictions.

However, field measurements suitable for validation of the MOIST model are essentially nonexistent. That is because in order to validate the model the field test facility has to be set up so that the characteristics and conditions are essentially the same as those assumed for the house and roof in the model. Thus, any field experiments must be conducted in sufficient detail to provide a suitable data set for model verification. That is not a trivial task. For example, the moisture and heat transfer properties of the materials used in the field test facility must be independently measured in the laboratory. That is because the properties of some materials such as plywood can vary by as much as an order of magnitude among different manufacturers. Furthermore, the air flow from the house into the attic and the attic ventilation must be measured to provide an attic ventilation correlation for the model.

Nonetheless, it would seem important to undertake field measurements to validate the MOIST Attic Model to check its predictions. Thus such a validation study is highly recommended.

ACKNOWLEDGMENTS

The authors thank Jeff Christian of Oak Ridge National Laboratory for recognizing the need to develop a roof moisture modeling capability and for funding this project. The authors appreciate the assistance of numerous individuals who provided information needed to formulate the computer input data, including Bill Rose of the University of Illinois Small Homes Council, Danny Parker of FSEC, and Dan Cautley and Peter Yost of the NAHB Research Center. In addition, the authors are indebted to a number of contributors from NIST: Jim Clifton and Ed Garboczi for reviewing the manuscript, Ray Mele for preparing the figures, and Paula Svincek for typing assistance.

NOMENCLATURE

Symbol	SI Units	English Units	Definition
A_f	m^2	ft^2	House floor area
A_n	m^2	ft^2	Area of surface n
B_1, B_2, B_3	-	-	Constants in sorption isotherm equation
c	J/kg·K	Btu/lb·°R	Specific heat
C_1, C_2, C_3	-	-	Constants in permeability equation
$C_{v,c}$	$(L/s)^2 \cdot cm^{-4} \cdot (m/s)^{-2}$	$cfm^2/in.^4 \cdot mph^2$	Wind coefficient for roof cavity
$C_{v,h}$	$(L/s)^2 \cdot cm^{-4} \cdot (m/s)^{-2}$	$cfm^2/in.^4 \cdot mph^2$	Wind coefficient for house
$C_{\Delta T,c}$	$(L/s)^2 \cdot cm^{-4} \cdot K^{-1}$	$cfm^2/in.^4 \cdot °F$	Stack coefficient for roof cavity
$C_{\Delta T,h}$	$(L/s)^2 \cdot cm^{-4} \cdot K^{-1}$	$cfm^2/in.^4 \cdot °F$	Stack coefficient for house
D_γ	m^2/s	ft^2/h	Liquid diffusivity
E	-	-	Emittance factor
ELA	cm^2	$in.^2$	Effective leakage area
h_{lv}	J/kg	Btu/lb	Latent heat of vaporization
$h_{c,i}$	$W/m^2 \cdot K$	$Btu/h \cdot ft^2 \cdot °R$	Convective heat transfer coefficient at inside surf.
$h_{c,n}$	$W/m^2 \cdot K$	$Btu/h \cdot ft^2 \cdot °R$	Convective heat transfer coef. at surface n
$h_{c,o}$	$W/m^2 \cdot K$	$Btu/h \cdot ft^2 \cdot °R$	Convective heat transfer coef. at outside surf.
$h_{r,i}$	$W/m^2 \cdot K$	$Btu/h \cdot ft^2 \cdot °R$	Radiative heat transfer coef. at inside surface
$h_{r,o}$	$W/m^2 \cdot K$	$Btu/h \cdot ft^2 \cdot °R$	Radiative heat transfer coefficient at outside surf.
H_c	m	ft	Stack height for roof cavity
H_h	m	ft	Stack height for house
H_{sol}	W/m^2	$Btu/h \cdot ft^2$	Incident solar radition onto a surface
k	W/m·K	Btu/h·ft·°R	Thermal conductivity
K	kg/m·s·Pa	lb/ft·h·inHg	Hydraulic conductivity
L_c	cm^2	$in.^2$	Effective leakage area for ceiling construction
L_e	cm^2	$in.^2$	Effective leakage area for stack effect air flow
L_h	cm^2	$in.^2$	Effective leakage area for whole house
L_i	cm^2	$in.^2$	Effective leakage area for any construction part
L_w	cm^2	$in.^2$	Effective leakage area for house below ceiling
L_r	cm^2	$in.^2$	Effective leakage area for roof construction
m_n	$kg/m^2 \cdot s \cdot Pa$	$lb/ft^2 \cdot h \cdot inHg$	Mass transfer coefficient at surface n
$M_{e,i}$	$kg/m^2 \cdot s \cdot Pa$	$lb/ft^2 \cdot h \cdot inHg$	Effective inside surface permeance
$M_{f,i}$	$kg/m^2 \cdot s \cdot Pa$	$lb/ft^2 \cdot h \cdot inHg$	Air film permeance at inside surface
$M_{p,i}$	$kg/m^2 \cdot s \cdot Pa$	$lb/ft^2 \cdot h \cdot inHg$	Paint permeance at inside surface
n	-	-	Hourly summation index or surface index
N	-	-	Current hour
p_l	Pa	inHg	Capillary pressure
p_v	Pa	inHg	Water vapor pressure
$p_{v,i}$	Pa	inHg	Water vapor pressure of indoor air
$p_{v,c}$	Pa	inHg	Water vapor pressure of cavity air
$p_{vs,n}$	Pa	inHg	Water vapor pressure at surface n
Δp_r	Pa	inHg	Stack effect reference pressure (4 Pa)
Δp_t	Pa	inHg	Total stack effect pressure head
t	s	h	Time
T	K	°R	Temperature
T_c	K	°R	Cavity air temperature
T_i	K	°R	Indoor temperature

Symbol	SI Units	English Units	Definition
T_m	K	°R	Mean temperature between the surface and the sky
$T_{s,n}$	K	°R	Temperature of surface n
T_{sky}	K	°R	Sky temperature
T_o	K	°R	Outdoor air temperature
v	m/s	mph	Average wind speed
$\dot{V}_{c\rightarrow o}$	m^3/s	cfm	Outdoor cavity ventilation rate
$\dot{V}_{h\rightarrow c}$	m^3/s	cfm	Air flow rate from house into cavity
$\dot{V}_{h,m}$	m^3/s	cfm	House mechanical ventilation rate
$\dot{V}_{h,n}$	m^3/s	cfm	House natural ventilation rate
$\dot{V}_{h,t}$	m^3/s	cfm	Total house ventilation rate
y	m	ft	Distance
$\dot{W}$	kg/s	lb/h	Moisture generation rate
Z(n)	-	-	Exponential weighting factors
$\propto$	-	-	Solar absorptance of exterior surface
γ	kg/kg	lb/lb	Moisture content on dry mass basis
ϵ_M	-	-	Convergence criteria for moisture solution
ϵ_T	-	-	Convergence criteria for thermal solution
κ	$kg/s\cdot m^2$	$lb/h\cdot ft^2$	Sorption constant per unit floor area
ρ_a	kg/m^3	lb/ft^3	Air density
ρ_d	kg/m^3	lb/ft^3	Dry material density
σ	$W/m^2\cdot K^4$	$Btu/h\cdot ft^2\cdot R^4$	Stefan-Boltzmann constant
μ	kg/m·s·Pa	lb/h·ft·inHg	Water vapor permeability
τ	s	h	Moisture storage time constant
ϕ	-	-	Relative humidity
ϕ_i	-	-	Indoor relative humidity
$\phi_{i,\tau}$	-	-	Hygric memory
ω_c	kg/kg	lb/lb	Cavity air humidity ratio
ω_i	kg/kg	lb/lb	Indoor air humidity ratio
ω_o	kg/kg	lb/lb	Outdoor air humidity ratio

REFERENCES

ASHRAE. 1993. *1993 ASHRAE Handbook - Fundamentals.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Bliss, R.W. 1961. "Atmospheric Radiation Near the Surface of the Ground." *Solar Energy*, Vol. 5, p. 103.

Buchan, Lawton, Parent Ltd. 1991. "Survey of Moisture Levels in Attics." Research Report BLP File No. 2497 submitted to Canada Mortgage and Housing Corporation; Ottawa, Ontario.

Burch, D.M. and Thomas, W.C. 1992. "An analysis of Moisture Accumulation in a Wood Frame Wall Subjected to Winter Climate," *Proceedings of Thermal Performance of the Exterior Envelopes of Buildings V*, ASHRAE/DOE/BTECC Conference, Dec. 7-10, Clearwater Beach, FL.

Burch, D.M. 1993. "An Analysis of Moisture Accumulation in Walls Subject to Hot and Humid Climates." *ASHRAE Transactions,* Vol. 99, No. 2.

Burch, D.M., Thomas, W.C., and Fanney, A.H. 1992. "Water Vapor Permeability Measurements of Common Building Materials." *ASHRAE Transactions*, 98(2).

Burch, D.M. 1995. "An Analysis of Moisture Accumulation in the Roof Cavities of Manufactured Housing," *Air Flow Performance of Building Envelopes, Components, and Systems, ASTM STP 1233*, American Society of Testing and Materials, Philadelphia, pp.156-177.

Burch, D., and Tsongas, G., and Walton, G. 1996. "A Mathematical Analysis of Practices to Control Moisture in the Roof Cavities of Manufactured Housing," NISTIR 5880, National Institute of Standards and Technology, September.

Carrol, J.A. 1980. "An 'MRT Method' of Computing Radiant Energy Exchange in Rooms." *Proceedings of the Second Systems Simulation and Economics Analysis Conference*. San Diego, CA, pp. 903-917.

Cleary, P., and Sherman, M. 1985, "Seasonal Storage of Moisture in Roof Sheathing," *Proceedings*, Moisture & Humidity 85 Conference, pp 313-323.

Climatic Atlas of the United States. 1983. National Oceanic and Atmospheric Administration; U.S. Department of Commerce, June.

Crow, L.W. 1981. "Development of Hourly Data for Weather Year for Energy Calculations (WYEC)." *ASHRAE Journal*, 23(10): 34-41.

Duffie, J.A. and Beckman, W.A. 1991. *Solar Engineering of Thermal Processes, Second Edition.* John Wiley & Sons, Inc.

Edwards, J.R. 1996. "Equilibrium Moisture Content Measurement for Porous Building materials at Various Temperatures." M.S. Thesis, mechanical Engineering Department, Virginia Polytechnic Institute & State University, May.

Greenspan, L. 1977. "Humidity Fixed Points of Binary Saturated Aqueous Solutions." *Journal of Research.* National Bureau of Standards (now National Institute of Standards and Technology), 81A(1): 89-96.

Harrje, D.T., Dutt, G.S., Gibson, R.G., Jacobson, D.I., and Hans, G. 1986. "Field Measurements of Seasonal Wood Moisture Variations in Residential Attics." *Proceedings*, Thermal Performance of the Exterior Envelopes of Buildings III, ASHRAE, pp. 620-633.

Hedlin, C.P. 1967. "Sorption Isotherms of Twelve Woods at Subfreezing Temperatures." *Forest Products Journal,* Vol. 17, No. 12.

International Energy Agency. 1990. Annex XIV, Condensation and Energy. Volume 2. *Guidelines and Practices.* August.

Lstiburek, J. and Carmody, J. 1991. "Moisture Control Handbook: New, Low-rise Residential Construction." ORNL/Sub/89-SD350/1, Oak Ridge National Laboratory.

Lstiburek, J.W. 1992a. "Mold and Mildew in Hotels and Motels: A Case Study Approach - Cooling Climates." *Proceedings of ASHRAE/DOE/BTECC Conference on Thermal Performance of the Exterior Envelopes of Buildings V.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Lstiburek, J.W. 1992b. "Moisture and Mildew in a Florida Health Facility." *Indoor Air Quality Update*, Vol. 5, No. 2, Cutter Information Corporation.

Lstiburek, J., and Carmody, J. 1993. *Moisture Control Handbook, Principles and Practices for Residential and Small Commercial Buildings*, Van Nostrand Reinhold, New York.

Olson, J., Schooler, S., and Mansfield, M. 1993. "Tri State Homes: A Case Study of Liability for Defective Homes which Created Unhealthy Environments Causing Personal Injuries." *Proceedings of International Conference on Building Design, Technology & Occupant Well-being in Temperate Climates*, Brussels, Belgium, February.

Palmiter, L., and Bond, T. 1991. "Interaction of Mechanical Systems and Natural Infiltration. *Proceedings, AIVC Conference on Air Movement and Ventilation Control Within Buildings.* Ottawa, Ont., Canada.

Parker, D.S., McIlvaine, J.E.R., Barkaszi, Jr. S.F., and Beal, D.J. 1993. "Laboratory Testing of Reflectance Properties of Roofing Materials." Florida Solar Energy Center, FSEC-CR-670-93, August.

Parker, D.S., Fairey, P.W., and Gu, L. 1991. "A Stratified Air Model for Simulation of Attic Thermal Performance." *Insulation Materials: Testing and Applications, 2nd Volume. ASTM STP 1116*. R.S. Graves and D.C. Wysocki, Eds., American Society for Testing and Materials, Philadelphia, 1991.

Pedersen, C.R. (now Carsten Rode). 1990. "Combined Heat and Moisture Transfer in Building Constructions." Report No. 214. Technical University of Denmark. September.

Richards, R.F., Burch, D.M., and Thomas, W.C. 1992. "Water Vapor Sorption Measurements of Common Building Materials." *ASHRAE Transaction, 98(2).*

Sherman, M.H. and D.T. Grimsrud. 1980. "Infiltration-Pressurization Correlation: Simplified Physical Modeling." *ASHRAE Transaction*, 86(2):778.

Sherwood, G.E. 1994. "Moisture - Related Properties of Wood and the Effect of Moisture on Wood and Wood Products." *ASTM Manual on Moisture Control in Buildings*. H. Trechsel (Ed.), American Society for Testing and Materials, Philadelphia, PA.

TenWolde, A. 1994. "Ventilation, Humidity, and Condensation in Manufactured Houses during Winter." *ASHRAE Transactions*, Volume 100, Part 1.

Threlkeld, J.L. 1970. *Thermal Environmental Engineering*. Prentice-Hall, New York. pp. 196-198.

Tsongas, G.A. 1990. "The Northwest Wall Moisture Study: A Field Study of Excess Moisture in Wall and Moisture Problems and Damage in New Northwest Homes," U.S. DOE/Bonneville Power Administration, Report No. DOE/BP-91489-1, June.

Tsongas, G., Burch, D., Roos, C., and Cunningham, M. 1995. "A Parametric Study of Wall Moisture Contents Using A Revised Variable Indoor Relative Humidity Version of the "MOIST" Transient Heat and Moisture Transfer Model," *Proceedings* of *Thermal Performance of the Exterior Envelopes of Buildings VI Conference*. Clearwater Beach, Florida.

U.S. Department of Housing and Urban Development. 1994. "Manufactured Home Construction and Safety Standards." *Code of Federal Regulations*, Title 24, Part 3280.

Walton, G.N. 1994. "CONTAM93 User Manual." NISTIR 5385. National Institute of Standards and Technology, March.